



University of Connecticut
OpenCommons@UConn

Doctoral Dissertations

University of Connecticut Graduate School

8-4-2020

Rectifiability of Pointwise Doubling Measures in Hilbert Space

Lisa Naples

University of Connecticut - Storrs, lisa.naples@uconn.edu

Follow this and additional works at: <https://opencommons.uconn.edu/dissertations>

Recommended Citation

Naples, Lisa, "Rectifiability of Pointwise Doubling Measures in Hilbert Space" (2020). *Doctoral Dissertations*. 2606.

<https://opencommons.uconn.edu/dissertations/2606>

Rectifiability of Pointwise Doubling Measures in Hilbert Space

Lisa Elizabeth Naples, Ph.D.

University of Connecticut, 2020

ABSTRACT

In geometric measure theory, there is interest in understanding the interactions of measures with rectifiable sets. Here, we study such interactions in three settings. First, we extend a theorem of Badger and Schul in Euclidean space to characterize rectifiable pointwise doubling measures in Hilbert space. Given a measure, we construct a multiresolution family of windows, and then we use a weighted Jones' function to record how well lines approximate the distribution of mass in each window. We show that when the measure is rectifiable, the mass is sufficiently concentrated around a line at each scale and that the converse also holds. We relay an algorithm for the construction of a rectifiable curve through appropriately chosen nets. Throughout, we discuss how to overcome the fact that in infinite dimensional Hilbert space there may be infinitely many points that are separated by a fixed distance even in a bounded set. Second, we prove a characterization for pointwise doubling measures which are carried by Lipschitz graphs. In this characterization, we show that if the mass in small neighborhoods of each typical point is sufficiently concentrated within a cone then the measure is carried by Lipschitz graphs, and, again, the converse holds as well. Finally, we discuss a notion of fractional rectifiability in which rectifiable curves are replaced by images of Hölder maps. We present a sufficient condition under which a pointwise doubling measure in infinite dimensional Hilbert space is carried by these Hölder images.

Rectifiability of Pointwise Doubling Measures in Hilbert Space

Lisa Elizabeth Naples

M.S. University of Connecticut 2016

B.S. Fairfield University 2014

A Dissertation

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

at the

University of Connecticut

2020

Copyright by

Lisa Elizabeth Naples

2020

APPROVAL PAGE

Doctor of Philosophy Dissertation

Rectifiability of Pointwise Doubling Measures in Hilbert Space

Presented by

Lisa Elizabeth Naples, B.S., M.S.

Major Advisor

Dr. Matthew Badger

Associate Advisor

Dr. Vasileios Chousionis

Associate Advisor

Dr. Lan-Hsuan Huang

University of Connecticut

2020

ACKNOWLEDGMENTS

First and foremost, I would like to thank my advisor, Matthew Badger, who has been part of my UConn experience from my very first graduate class. In addition to guiding me through course content and academic research, Matthew has taught me to seek out opportunities to share my work, and he has been a role model in demonstrating how to balance research with other professionals responsibilities. The most common piece of advice I received heading into graduate school was to choose my advisor carefully. Reflecting on my experience, I am sure I made the right choice.

There are many other people who have helped me along the way to my degree. I would like to recognize the members of my dissertation committee, Vasileios Chousionis and Lan-Hsuan Huang for their guidance and support. They, along with several other professors in the department, have been invaluable contributors to my learning experiences at UConn. I would also like to recognize the administrative staff in the UConn math department, who consistently made themselves available to answer any questions and to keep me on top of deadlines. Finally, I would like to acknowledge the Fairfield University math department professors and the Wallingford Public School District teachers who saw potential in me that I did not always see in myself and who encouraged me to continue to pursue education beyond what I thought were my limits.

I am grateful for the support of friends who I have leaned on over the past six years. In particular, Jieun Lee, Junqing Qian (and Puffy), Qintian Sun, and Ximo Zhang have walked with me through each stage of the Ph.D. program. In addition to those that have been by my side physically, I have found comfort in knowing that I have had many friends cheering me on from afar.

Lastly, I would like to thank my family for the continued support throughout my academic journey. I am blessed with a network of grandparents, aunts, uncles, and cousins, and the time that I spend with them always serves as a reminder to me that there are much greater things in this world than math. I am especially thankful to my parents, Susan and Paul, for providing me with a home that I love to come back to; to my brothers, Brian and Paul Jr., for teaching me the resilience that got me through my graduate studies; and to my dog, Lucy, for filling the past three years of my life with adventure and laughter.

Contents

Ch. 1. Introduction	1
1.1 The Identification Problem	1
1.2 History	3
1.3 Main Results	7
1.3.1 Rectifiable measures	7
1.3.2 Graph rectifiable measures	10
1.3.3 Hölder rectifiable measures	12
1.4 Organization	15
Ch. 2. Standard measure theory results for pointwise doubling measures	16
2.1 Covering and density theorems for pointwise doubling measures	16
2.2 Hausdorff and Packing Measures	21
2.3 Finite overlap property	24
Ch. 3. Rectifiable measures	26
3.1 Necessary Condition	26
3.2 Sufficient condition for rectifiability	37
3.3 The decomposition of μ	49
3.4 An example of a rectifiable pointwise doubling measure with infinite dimensional support	50
Ch. 4. Drawing curves through nets: an Analyst's Traveling Salesman Algorithm	53
4.1 Description of curves	56
4.2 Connectedness	61
4.3 Length estimates	65
Ch. 5. Graph rectifiable measures	77

Ch. 6. Hölder parametrization and fractional rectifiability	85
6.1 Hölder curves through nets	85
6.2 Fractional rectifiability of measures	86
Bibliography	92

Chapter 1

Introduction

1.1 The Identification Problem

One goal of geometric measure theory is to understand the global structure of a measure through analysis of local geometric data. We use the below terminology to formalize this notion.

Definition 1.1.1. Let $(\mathbb{X}, \mathcal{M})$ be a measurable space, and let $\mathcal{N} \subset \mathcal{M}$ be a family of measurable sets. We say

1. μ is carried by \mathcal{N} if there exist countably many $N_i \in \mathcal{N}$ such that $\mu(\mathbb{X} \setminus \bigcup_i N_i) = 0$;
2. μ is singular to \mathcal{N} if $\mu(N) = 0$ for every $N \in \mathcal{N}$.

A σ -finite measure μ on $(\mathbb{X}, \mathcal{M})$ can be decomposed uniquely as

$$\mu = \mu_{\mathcal{N}} + \mu_{\mathcal{N}}^{\perp}$$

where $\mu_{\mathcal{N}}$ is carried by \mathcal{N} and $\mu_{\mathcal{N}}^{\perp}$ is singular to \mathcal{N} . We provide three examples to the demonstrate

the notions of being carried by and being singular to a collection \mathcal{N} . To construct these examples, we will use Hausdorff measures. The definition of Hausdorff measures can be found in Chapter 2.

Example 1.1.1 (See [5, Example 1.2]). Let $\{p_i\}_{i=0}^\infty$, $\{\ell_i\}_{i=0}^\infty$, and $\{s_i\}_{i=0}^\infty$ be dense collections of points, unit line segments, and unit squares, respectively, in \mathbb{R}^2 . Let $\{a_i\}_{i=0}^\infty$ be a sequence of positive real numbers such that $\sum_{i=0}^\infty a_i = 1$. Define

$$\mu_0 = \sum_{i=0}^\infty a_i \mathcal{H}^0 \llcorner p_i, \quad \mu_1 = \sum_{i=0}^\infty a_i \mathcal{H}^1 \llcorner \ell_i, \quad \text{and} \quad \mu_2 = \sum_{i=0}^\infty a_i \mathcal{H}^2 \llcorner s_i.$$

Here $\mathcal{H}^m \llcorner A$ denotes the restriction of \mathcal{H}^m to the set A ; that is, $\mathcal{H}^m \llcorner A(B) = \mathcal{H}^m(A \cap B)$ for every measurable set B . Recall that the support of a Borel measure μ , $\text{spt}(\mu)$, on \mathbb{X} is the largest closed subset of \mathbb{X} such that for all x in the subset, every neighborhood of x has positive measure. In this example, $\text{spt}(\mu_0) = \text{spt}(\mu_1) = \text{spt}(\mu_2) = \mathbb{R}^2$. However, μ_0 is carried by the collection of points $\{p_i\}$ whereas μ_1 and μ_2 are each singular to that collection and to any other countable collection of points. Furthermore, both μ_0 and μ_1 are carried by the collections of unit line segments in \mathbb{R}^2 . In particular, for μ_0 take $\{\ell'_i\}$ such that ℓ'_i intersects p_i , and for μ_1 take $\{\ell_i\}$. On the other hand, μ_2 is singular to any countable collection of line segments. We see through these examples that by studying the carrying sets of measures we can obtain a more precise understanding of the geometric structure of measures when compared to studying the support.

In [5], Badger poses the following problem about carrying sets:

Problem 1.1.1 (Identification Problem). Let $(\mathbb{X}, \mathcal{M})$ be a measurable space, let $\mathcal{N} \subset \mathcal{M}$ be a family of measurable sets, and let \mathcal{F} be a family of σ -finite measures defined on \mathcal{M} . Find properties $P(\mu, x)$ and $Q(\mu, x)$ defined for all $\mu \in \mathcal{F}$ and $x \in \mathbb{X}$ such that

$$\mu_{\mathcal{N}} = \mu \llcorner \{x \in \mathbb{X} : P(\mu, x) \text{ holds}\} \quad \text{and} \quad \mu_{\mathcal{N}}^\perp = \mu \llcorner \{x \in \mathbb{X} : Q(\mu, x) \text{ holds}\}.$$

That is, we seek to find pointwise properties $P(\mu, x)$ and $Q(\mu, x)$ that identify the part of μ where the underlying geometric structure agrees with the structure of sets in \mathcal{N} and the part of μ where the underlying geometric structure is distinct from that of the sets in \mathcal{N} . There is particular interest in understanding the conditions under which measures can be decomposed when \mathbb{X} is a metric space, \mathcal{M} contains the Borel sets, and \mathcal{N} is the collection of *rectifiable curves*, that is, compact, connected sets of finite length or, equivalently, finite \mathcal{H}^1 measure. Measures which are carried by the collection of rectifiable curves are called *rectifiable measures*, and measures which are singular to the collection of rectifiable curves are called *purely unrectifiable measures*. We use the notation

$$\mu = \mu_{\text{rect}} + \mu_{\text{pu}} \tag{1.1.1}$$

to indicate decomposition of a measure μ into a rectifiable component and a purely unrectifiable component.

1.2 History

The study of rectifiable measures stems from the study of rectifiable sets. A *rectifiable set* is a set which is contained \mathcal{H}^1 -a.e. in a countable union of rectifiable curves. Given an arbitrary set in \mathbb{R}^n of finite length, we cannot expect the set to admit tangent lines at typical points. However, a rectifiable set can inherit the tangent lines from the rectifiable curve in which it is contained. In particular, recall that a map $f : [0, 1] \rightarrow \mathbb{R}^n$ is called Lipschitz if $|f(x) - f(y)| \leq L|x - y|$ for all $x, y \in [0, 1]$. The class of rectifiable curves agrees with the class of images of the unit interval under Lipschitz maps. See, for example, [2]. By Rademacher's Theorem, a Lipschitz map $f : [0, 1] \rightarrow \mathbb{R}^n$ is differentiable \mathcal{L}^1 -a.e., and thus at \mathcal{H}^1 -a.e. $x \in f([0, 1])$ there is a unique tangent line given by the derivative map.

The notion of rectifiable sets in the plane was originally introduced by Besicovitch [10]. Morse and Randolph [27] and Federer [16] extended the concept of rectifiable sets to measures in Euclidean space. Since then a large theory has been developed for identifying rectifiable measures (and their higher-dimensional analogues) μ under the additional assumption of absolute continuity of μ with respect to 1-dimensional Hausdorff measure ($\mu \ll \mathcal{H}^1$). Imposing the absolute continuity assumption on measures allows one to replace the class of Lipschitz images with the class of bi-Lipschitz images or Lipschitz graphs in the definition of rectifiable measure. For results in this direction see [25], [29], [3], [4], [12] and [13]. However, Garnett, Killip, and Schul [18] constructed a doubling measure on \mathbb{R}^n which is both carried by Lipschitz images and singular to every bi-Lipschitz image. Thus they showed that the class of measures carried by bi-Lipschitz images is strictly smaller than the class of measures carried by Lipschitz images. In what follows, we adopt Federer's convention [16], [17] and do not assume a priori that μ is absolutely continuous with respect to \mathcal{H}^1 .

Jones' beta numbers for sets were originally introduced by Peter Jones [20] as a means to solve his Analyst's Traveling Salesman Problem that asked to give necessary and sufficient conditions for a set to be contained in a single rectifiable curve. Jones provided a solution to his problem for sets in \mathbb{R}^2 and Okikiolu [28] extended the result to \mathbb{R}^n . Later, Schul [30] extended Jones' result to Hilbert space. We summarize the Analyst's Traveling Salesman result for Hilbert space here.

Definition 1.2.1 (Beta number). Let $E \subset H$, where H is a separable, infinite dimensional Hilbert space or \mathbb{R}^n , and let $Q \subset H$ be bounded. We define $\beta_E(Q) \in [0, 1]$ by

$$\inf_{\ell} \sup_{x \in E \cap Q} \frac{\text{dist}(x, \ell)}{\text{diam } Q},$$

where the infimum ranges over all lines ℓ in H . If $E \cap Q = \emptyset$, we set $\beta_E(Q) = 0$.

The beta numbers measure how well the set E is approximated by a line in the window Q .

In Euclidean space, dyadic cubes are often a practical choice for windows. However, in infinite dimensional Hilbert space, such cubes are no longer practical because, for examples, $[0, 1] \times [0, 1] \times \dots$ does not live in ℓ^2 . To prove an Analyst's Traveling Salesman theorem, Schul replaced dyadic cubes with a *multiresolution family of balls* \mathcal{G}^K for a set bounded $K \subset H$, defined as follows. Fix k_0 such that $2^{k_0} \geq \text{diam}(K)$. For each $k \geq k_0$, let $N_k^K \supset N_{k-1}^K$ be a maximal 2^{-k} -net for K . Set $U_{k,i} := B(n_i, \lambda_1 2^{-k})$ to be the closed ball of radius $\lambda_1 2^{-k}$ centered at $n_i \in N_k$; we specify $\lambda_1 > 1$ later. We denote the collection of balls arising from the nets N_k^K by \mathcal{G}_k^K , and we set

$$\mathcal{G}^K = \bigcup_{k=k_0}^{\infty} \mathcal{G}_k^K.$$

Unlike dyadic cubes which are intrinsic to Euclidean space, the multiresolution family depends on the set K as well as on the specific choices of the nets N_k^K .

Theorem 1.2.1 (Analyst's Traveling Salesman Theorem [30, Theorem 1.1 and Theorem 1.5]).

1. (Necessary Condition) Let Γ be any connected set containing K . Then

$$\sum_{U \in \mathcal{G}^K} \beta_{\Gamma}^2(U) \text{diam}(U) \lesssim \mathcal{H}^1(\Gamma).$$

The constant behind the symbol \lesssim depends only on the choice of λ_1 .

2. (Sufficient Condition) There is a constant λ_0 such that for all $\lambda_1 > \lambda_0$ and for any set $K \subset H$ there exists a connected set $\Gamma_0 \supset K$ satisfying

$$\mathcal{H}^1(\Gamma_0) \lesssim \text{diam}(K) + \sum_{U \in \mathcal{G}^K} \beta_K^2(U) \text{diam}(U).$$

Here we require $2^{-k_0} \geq \text{diam}(K)$.

For the study of rectifiable measures Jones' beta numbers may be replaced by an L^2 variant, introduced by David and Semmes in [14], [15].

Definition 1.2.2 (L^2 beta number). Let μ be a locally finite Borel measure on H , a separable infinite dimensional Hilbert space or \mathbb{R}^n . Let $E \subset H$ be a bounded subset. We define $\beta_2(\mu, E)$ by

$$\beta_2^2(\mu, E) = \inf_{\ell} \int_E \left(\frac{\text{dist}(x, \ell)}{\text{diam } E} \right)^2 \frac{d\mu(x)}{d\mu(E)}$$

where the infimum is taken over all lines ℓ in H . In the case that $\mu(E) = 0$, we define $\beta_2(\mu, E) = 0$.

The L^2 beta numbers weigh the distances of points from a line according to the mass distribution of μ in a particular window E . To prove results about rectifiability of measures on Euclidean space \mathbb{R}^n Badger and Schul, in [7] and [8], recorded beta numbers on the collection of half-open dyadic cubes of side length at most one, $\Delta_1(\mathbb{R}^n)$, using the density-normalized L^2 Jones function $\tilde{J}_2(\mu, \cdot)$ defined by

$$\tilde{J}_2(\mu, x) := \sum_{Q \in \Delta_1(\mathbb{R}^n)} \beta_2^2(\mu, 3Q) \frac{\text{diam } Q}{\mu(Q)} \chi_Q(x)$$

for all $x \in \mathbb{R}^n$. Similar to above, when $\mu(Q) = 0$, we interpret $\beta_2^2(\mu, 3Q) \text{diam } Q / \mu(Q) = 0$. Although Badger and Schul proved results for general Radon measures, here we only state their result for pointwise doubling measures, which has lighter notation.

Theorem 1.2.2 ([8, Theorem E]). *Let $n \geq 2$. If μ is a Radon measure on \mathbb{R}^n such that at μ -a.e. x*

$$\limsup_{r \downarrow 0} \mu(B(x, 2r)) / \mu(B(x, r)) < \infty$$

then the decomposition $\mu = \mu_{\text{rect}} + \mu_{\text{pu}}$ is given by

$$\mu_{\text{rect}} = \mu \llcorner \{x \in \mathbb{R}^n : \tilde{J}_2(\mu, x) < \infty\} \text{ and } \mu_{\text{pu}} = \mu \llcorner \{x \in \mathbb{R}^n : \tilde{J}_2(\mu, x) = \infty\}. \quad (1.2.1)$$

1.3 Main Results

1.3.1 Rectifiable measures

We extend the results of Badger and Schul to pointwise doubling measures on a separable infinite dimensional Hilbert space, H . Following [30], we replace the dyadic cubes used in the Euclidean case with a multiresolution family of balls. However, we construct the multiresolution family with respect to a carrying set of μ . Fix some such set $X \subset H$ so that $\mu(H \setminus X) = 0$. For example, we may choose $X = \text{spt}(\mu)$. Then fix an integer k_0 . We denote a maximal 2^{-k} -net of X by X_k^μ . We choose the nets X_k^μ to be nested so that $X_{k+1}^\mu \supset X_k^\mu$ for all $k \geq k_0$. For a net X_k^μ , we define an associated collection of closed balls,

$$\mathcal{C}_k^\mu = \{B(x_k^j, \lambda_2 2^{-k}) : x_k^j \in X_k^\mu\},$$

where $\lambda_2 > 1$ is some fixed constant. We will specify conditions on λ_2 later in the exposition.

Then we set

$$\mathcal{C}^\mu := \bigcup_{k=k_0}^{\infty} \mathcal{C}_k^\mu,$$

and we call \mathcal{C}^μ a *multiresolution family of balls for the measure μ* . We emphasize that the collection \mathcal{C}^μ is dependent on the measure μ and more specifically on the choice of nets X_k^μ . We use the notation

$$B_k^j := B(x_k^j, \lambda_2 2^{-k}),$$

and for a fixed ball $B \in \mathcal{C}^\mu$, we denote the center by x_B . For $c > 0$, we define

$$cB_k^j := B(x_k^j, c\lambda_2 2^{-k}).$$

That is, cB is the dilation of ball B by a factor of c .

We define the L^2 density adapted Jones function $\hat{J}(\mu, \cdot)$ on H to be

$$\hat{J}_2(\mu, x) := \sum_{\substack{B \in \mathcal{C}^\mu \\ \text{Radius}(B) \leq \lambda_2}} \beta_2^2(\mu, 2B) \frac{\text{diam } B}{\mu(B)} \chi_B(x)$$

for all $x \in H$. Before we state our main results we also define pointwise doubling measures on H .

Definition 1.3.1 (Pointwise doubling measure). We say a measure μ on H is *pointwise doubling* if μ is a Borel regular outer measure that is finite on bounded sets, and for μ -a.e. x ,

$$\limsup_{r \downarrow 0} \frac{\mu(B(x, 2r))}{\mu(B(x, r))} < \infty.$$

Furthermore, we say that μ is a *doubling measure* if there exists a constant D such that for all $r > 0$ and μ -a.e. x , $\mu(B(x, 2r)) \leq D\mu(B(x, r))$.

Theorem A (Characterization of rectifiable doubling measures). Let μ be a pointwise doubling measure on a separable, infinite dimensional Hilbert space H . Then μ is rectifiable if and only if

$$\hat{J}_2(\mu, x) < \infty \text{ for } \mu\text{-a.e. } x \in H.$$

We will freely refer to the *necessary condition* and the *sufficient condition* of Theorem A.

Necessary condition: If μ is rectifiable, then $\hat{J}_2(\mu, x) < \infty$ for μ -a.e. $x \in H$.

Sufficient condition: If $\hat{J}_2(\mu, x) < \infty$ for μ -a.e. x , then μ is rectifiable.

Theorem B (Decomposition theorem for doubling measures). Let μ be a pointwise doubling measure on a separable, infinite dimensional Hilbert space H . Then the decomposition $\mu = \mu_{\text{rect}} + \mu_{\text{pu}}$

is given by

$$\mu_{\text{rect}} = \mu \llcorner \{x \in H : \hat{J}_2(\mu, x) < \infty\} \text{ and } \mu_{\text{pu}} = \mu \llcorner \{x \in H : \hat{J}_2(\mu, x) = \infty\}.$$

One of the challenges of proving these results in infinite dimensional space as opposed to \mathbb{R}^n arises in the differences between the multiresolution family of balls and dyadic cubes. In particular, the set of dyadic cubes satisfies convenient counting properties. For a given half-open dyadic cube $Q \in \mathbb{R}^n$ of side length 2^{-k} , there are 2^n dyadic cubes of side length $2^{-(k+1)}$ contained in Q . Additionally, cQ intersects at most $C(c, n)$ other cubes of side length 2^{-k} where $C(c, n)$ is a constant which depends only on the dilation constant c and the dimension of the space n . The pointwise doubling condition assumed on μ allows us to recover some of the counting properties of dyadic cubes for subcollections of \mathcal{C}^μ .

The sufficient direction of the proof of Theorem A relies on the construction of a rectifiable curve using beta numbers to determine how to connect net points in windows. A constructive algorithm for such curves in Euclidean space was presented by Jones [20] in his proof of the Analyst's Traveling Salesman Theorem. The algorithm was adapted to infinite dimensional Hilbert space by Schul [30] who removed the dimensional dependence by more carefully estimating the length of the curve in windows with large beta numbers. Badger and Schul [8] added flexibility to the algorithm in the Euclidean setting by removing an assumption that subsequent generations of net points be nested. This flexibility is essential to applications in the setting of measures. In the following theorem, we have removed the dimension dependence of constants in the algorithm presented in [8] by employing ideas from [30] and [6].

Theorem C. Let H be a separable, infinite dimensional Hilbert space. Let $C^* > 1$, let $x_0 \in H$, $0 < \delta \leq 1/2$, and $r_0 > 0$. Let $\{V_k\}_{k=0}^\infty$ be a sequence of nonempty, finite subsets of $B(x_0, C^* r_0)$ such that

(V1) distinct points $v, v' \in V_k$ are uniformly separated: $|v - v'| \geq \delta^k r_0$.

(V2) for all $v_k \in V_k$, there exists $v_{k+1} \in V_{k+1}$ such that $|v_{k+1} - v_k| < C^* \delta^k r_0$.

(V3) for all $v_k \in V_k$ there exists $v_{k-1} \in V_{k-1}$ such that $|v_{k-1} - v_k| < C^* \delta^k r_0$.

Suppose that for all $k \geq 1$ and for all $v \in V_k$, we are given a straight line $\ell_{k,v}$ in H and a number $\alpha_{k,v} \geq 0$ such that

$$\sup_{x \in (V_{k-1} \cup V_k) \cap B(v, 66C^* \delta^{k-2} r_0)} \text{dist}(x, \ell_{k,v}) \leq \alpha_{k,v} \delta^k r_0,$$

and

$$\sum_{k=1}^{\infty} \sum_{v \in V_k} \alpha_{k,v}^2 \delta^k r_0 < \infty.$$

Then the sets V_k converge in the Hausdorff metric to a compact set $V \subset B(x_0, C^* r_0)$, and there exists a compact connected set $\Gamma \subset \overline{B(x_0, C^* r_0)}$ such that $\Gamma \supset V$ and

$$\mathcal{H}^1(\Gamma) \lesssim_{C^*, \delta} r_0 + \sum_{k=1}^{\infty} \sum_{v \in V_k} \alpha_{k,v}^2 \delta^k r_0.$$

1.3.2 Graph rectifiable measures

As illustrated by the example in [18], characterizing measures which are carried by Lipschitz graphs is a distinct problem from characterizing measures which are carried by Lipschitz images. We define Lipschitz graphs in the following way. Let V be an m -dimensional plane in H . Let $f : V \rightarrow V^\perp$ be a L -Lipschitz map. Then the set $\Gamma = \{(v, f(v)) : v \in V\}$ is an L -Lipschitz graph in H . Lipschitz graphs are characterized by having cone points everywhere in the following sense. Define the *good cone* at x with respect to V and α by

$$C_G(x, V, \alpha) := \{y \in H : \text{dist}(y - x, V) \leq \alpha |x - y|\},$$

and the bad cone at x with respect to V and α by

$$C_{\mathcal{B}}(x, V, \alpha) := H \setminus C_{\mathcal{G}}(x, V, \alpha).$$

For an L -Lipschitz graph and for $x \in \Gamma$, $\Gamma \cap C_{\mathcal{B}}(x, V, \alpha) = \emptyset$ where α depends on the Lipschitz constant.

In [24] Martín and Mattila study sets $E \subset \mathbb{R}^n$ with $0 < \mathcal{H}^s(E) < \infty$ and $0 < s < m \leq n - 1$, where s is allowed to be non-integer valued. They define the set E to be (s, m) -approximately conically regular if for \mathcal{H}^s -a.e. $x \in E$, there exists an m -plane V and $\alpha \in (0, 1)$ such that

$$\lim_{r \downarrow 0} \frac{\mathcal{H}^s(E \cap C_{\mathcal{B}}(x, r, V, \alpha))}{r^s} = 0. \quad (1.3.1)$$

where $C_{\mathcal{B}}(x, r, V, \alpha)$ denotes $C_{\mathcal{B}}(x, V, \alpha) \cap B(x, r)$. Furthermore, they prove that an s -set which is (s, m) -approximately conically regular is carried \mathcal{H}^s -a.e. by m -Lipschitz graphs. Condition (1.3.1) serves as an inspiration for the following characterization of graph rectifiable measures, that is, measures carried by Lipschitz graphs.

Theorem D. Let μ be a pointwise doubling measure on a separable, finite or infinite dimensional Hilbert space H . For μ -a.e. $x \in H$ there is an m -plane V and an $\alpha \in (0, 1)$ such that

$$\lim_{r \downarrow 0} \frac{\mu(C_{\mathcal{B}}(x, r, V, \alpha))}{\mu(B(x, r))} = 0 \quad (1.3.2)$$

if and only if μ is carried by Lipschitz graphs.

To explicitly see the connection to the condition (1.3.1) and condition (1.3.2), we remark that

given a set $E \subset \mathbb{R}^n$ with $0 < \mathcal{H}^s(E) < \infty$,

$$\limsup_{r \downarrow 0} \frac{\mathcal{H}^s(E \cap B(x, r))}{r^s} < c < \infty \text{ for } \mu\text{-a.e. } x \in \mathbb{R}^n.$$

It follows that if

$$\lim_{r \downarrow 0} \frac{\mathcal{H}^s \llcorner E(C_{\mathcal{B}}(x, r, V, \alpha))}{\mathcal{H}^s \llcorner E(B(x, r))} = \lim_{r \downarrow 0} \frac{\mathcal{H}^s(E \cap C_{\mathcal{B}}(x, r, V, \alpha))}{\mathcal{H}^s(E \cap B(x, r))} = 0$$

then

$$\lim_{r \downarrow 0} \frac{\mathcal{H}^s(E \cap C_{\mathcal{B}}(x, r, V, \alpha))}{r^s} = 0.$$

For additional results on densities of measures with respect to cones, see [11], [21], and [22].

Graph rectifiability also plays a role in the study of harmonic measure. See e.g. [1].

1.3.3 Hölder rectifiable measures

Theorem A and Theorem B above provide necessary and sufficient conditions under which a measure is carried by a specific class of 1-dimensional sets, namely the class of rectifiable curves. The proofs of these theorems are reliant on the existence of Analyst's Traveling Salesman results that classify sets which are contained in rectifiable curves. There is also interest in understanding the interaction of measures with classes of higher dimensional sets. In addition to the Lipschitz graphs, another such class of sets of higher dimensional sets is images of the unit interval under Hölder maps.

Definition 1.3.2 (Hölder map). A map $f : [0, 1] \rightarrow H$ is $1/s$ -Hölder if $|f(x) - f(y)| \leq h|x - y|^{1/s}$ for all $x, y \in [0, 1]$. Here h is independent of x and y .

Unlike Lipschitz maps, Hölder maps may increase dimension. In particular, the image of the

(1-dimensional) unit interval under a $1/s$ -Hölder map may increase to at most an s -dimensional set. In [6], the author, together with Badger and Vellis provide a construction algorithm of Hölder maps whose image contain sets of net points in Hilbert space. For a fixed constant $C^* > 1$, nets are chosen to satisfy the following properties:

(V0') When $k = 0$, we have $\rho_0 = 1$. For all $k \geq 0$, we have $\xi_1 \rho_k \leq \rho_{k+1} \leq \xi_2 \rho_k$ where $0 \leq \xi_1 \leq \xi_2 < 1$.

(V1') When $k = 0$, we have $V_0 \subset B(x_0, C^* r_0)$.

(V2') For all $k \geq 0$, we have $V_k \subset V_{k+1}$.

(V3') For all $k \geq 0$ and all distinct $v, v' \in V_k$, we have $|v - v'| \geq \rho_k r_0$.

(V4') For all $k \geq 0$ and all $v \in V_{k+1}$, there exists $v' \in V_k$ such that $|v - v'| < C^* \rho_{k+1} r_0$.

(V5') For each $k \geq 0$ and $v \in V_k$ we are given a number $\alpha_{k,v} \geq 0$ and a straight line $\ell_{k,v}$ in H such that for $A^* = \frac{C^*}{1-\xi_2}$,

$$\sup_{x \in V_{k+1} \cap B(v, 30A^* \rho_k r_0)} \text{dist}(x, \ell_{k,v}) \leq \alpha_{k,v} \rho_{k+1} r_0.$$

The algorithm also uses the notion of variation excess.

Definition 1.3.3 (variation excess, [6, Definition 2.6]). For all $s \geq 1$, for all $k \geq 0$, and for all $(v, v') \in \text{Flat}(k)$, define the s -variation excess $\tau_s(k, v, v')$ by

$$\tau_s(k, v, v') |v - v'|^s = \max \left\{ \left(\sum_{i=1}^{n-1} |v_{i+1} - v_i|^s \right) - |v - v'|^s, 0 \right\},$$

where $V_{k+1}(v, v') = \{v_1, \dots, v_n\}$ with $v_1 = v$, $v_n = v'$, and v_{i+1} is the first point to the right (or left) of v_i for all $1 \leq i \leq n-1$.

When $s > 1$, then the variation excess is zero whenever the set $V_{k+1}(v, v')$ lives in a sufficiently flat tube; see [6, Lemma 2.8]. This property is essential for the proof of the Traveling Salesman theorem.

Theorem 1.3.1 (Hölder Traveling Salesman with Nets, [6, Theorem 5.1]). *Assume that H is a separable infinite dimensional Hilbert space or \mathbb{R}^n for some $n \geq 2$. Let $s \geq 1$, let $\mathcal{V} = (V_k, \rho_k)_{k \geq 0}$ be a sequence of finite sets V_k in H and numbers $\rho_k > 0$ that satisfy properties (V0')-(V5'). If $\alpha_0 \in \left(0, \min \left\{ \frac{1}{16}, \left(\frac{\xi_1(1-\xi_2)}{42C^*} \right)^{1/2} \right\} \right)$ and*

$$S_{\mathcal{V}}^s := \sum_{k=0}^{\infty} \sum_{(v,v') \in Flat(k)} \tau_s(k, v, v') \rho_k^s + \sum_{k=0}^{\infty} \sum_{\substack{v \in V_k \\ \alpha_{k,v} \geq \alpha_0}} \rho_k^s < \infty, \quad (1.3.3)$$

then there exists a $(1/s)$ -Hölder map $f : [0, 1] \rightarrow H$ such that $f([0, 1]) \supset \bigcup_{k \geq 0} V_k$ and the Hölder constant of f satisfies $h \lesssim_{s, C^, \xi_1, \xi_2} r_0(1 + S_{\mathcal{V}}^s)$.*

Although we omit the proof of the Hölder Traveling Salesman theorem in this dissertation, we do present full details of the following theorem which is an application of Theorem 1.3.1.

Theorem E. Let μ be a pointwise doubling Radon measure on H , a separable infinite dimensional Hilbert space or \mathbb{R}^n , let $s > 1$, and let $p, q > 0$. Then

$$\mu \llcorner \left\{ x \in H : \int_0^1 \beta_p^{(1)}(\mu, x, r)^q \frac{r^s}{\mu(B(x, r))} \frac{dr}{r} < \infty \right\}$$

is carried by $(1/s)$ -Hölder curves.

Unlike the case for rectifiable curves, there is no necessary condition for a $1/s$ -Hölder curve in terms of beta numbers; see [6, Section 9.1]. Hence the measure theoretic result provides only a sufficient condition for a measure to be carried by $(1/s)$ -Hölder curves rather than a characterization.

1.4 Organization

This dissertation contains five additional chapters. In Chapter 2 we collect some basic measure theory definitions and results that will be used throughout. Chapters 3 and 4 are devoted to characterizing rectifiable measures in Hilbert space. In particular, in Chapter 3 we present the results on rectifiable pointwise doubling measures and in Chapter 4 we present the proof of the Analyst's Traveling Salesman Theorem used to prove the sufficient condition of the characterization of rectifiable measures. In Chapter 5 we discuss graph rectifiability. Finally in Chapter 6 we present results on fractional rectifiability.

Chapter 2

Standard measure theory results for pointwise doubling measures

In this chapter we collect extensions of results which are standard for measures in Euclidean space to the setting of pointwise doubling measures in Hilbert space. The results for Euclidean space and other metric space can be found in many textbooks. See, for example, [26] or [19].

2.1 Covering and density theorems for pointwise doubling measures

The goal of this section is to prove the following density theorem.

Theorem 2.1.1. *Let μ be a pointwise doubling measure on a separable infinite dimensional Hilbert space H . Let $A \subset H$ such that for μ -a.e. $x \in A$,*

$$\mu(B(x, 2r)) \leq D\mu B(x, r).$$

Then for any $A' \subset A$,

$$\lim_{r \downarrow 0} \frac{\mu(A' \cap B(x, r))}{\mu(B(x, r))} = 1 \text{ for } \mu\text{-a.e. } x \in A'.$$

To complete the proof, we will need a series of preliminary results. We begin by stating the $5r$ covering theorem which holds in arbitrary metric spaces; we omit the proof and refer the interested reader to e.g. [19],

Theorem 2.1.2. *Let \mathcal{F} be a family of closed balls in a metric space (X, d) such that $M := \sup\{\text{radius}(B) : B \in \mathcal{F}\} < \infty$. Then there exists a subfamily $\mathcal{G} \subset \mathcal{F}$ such that*

1. \mathcal{G} is pairwise disjoint;
2. $\bigcup_{B \in \mathcal{F}} B \subset \bigcup_{B' \in \mathcal{G}} 5B'$;
3. Every ball $B \in \mathcal{F}$ intersects a ball from \mathcal{G} with radius at least half that of B .

Next we prove an adaptation of Vitali covering theorem for pointwise doubling measures.

Theorem 2.1.3. *Let μ be a pointwise doubling measure on a separable, infinite dimensional space H . Let $A \subset H$ be a bounded set such that for μ -a.e. $x \in A$*

$$\mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for all } r \in (0, 1].$$

Let \mathcal{B} be a collection of closed balls centered on A of radius $0 < r < 1/5$ such that for each $x \in A$, $\inf\{r : B(x, r) \in \mathcal{F}\} = 0$. Then there exists a disjoint family $\mathcal{G} = \{B_1, B_2, \dots\} \subset \mathcal{F}$ such that $\mu\left(A \setminus \bigcup_{j=1}^{\infty} B_j\right) = 0$.

Proof. By Theorem 2.1.2, we obtain a family $\mathcal{G} \subset \mathcal{F}$ of pairwise disjoint balls such that $\bigcup_{B \in \mathcal{F}} B \subset \bigcup_{B' \in \mathcal{G}} 5B'$ and such that every ball $B \in \mathcal{F}$ intersects a ball in \mathcal{G} with radius at least half that of B .

Now

$$\sum_{B' \in \mathcal{G}} \mu(5B') \leq D^3 \sum_{B' \in \mathcal{G}} \mu(B') \leq C^3 \mu(\mathcal{N}_1(A))$$

where $\mathcal{N}_1(A) = \{x : \text{dist}(x, A) \leq 1\}$. Since A is bounded, $\mathcal{N}_1(A)$ is also bounded and hence has finite measure. In particular, this implies $\sum_{B' \in \mathcal{G}} \mu(5B') < \infty$ so \mathcal{G} can be taken to be at most a countable collection. Enumerate the elements of $\mathcal{G} = \{B_1, B_2, \dots\}$. We then have

$$\lim_{N \rightarrow \infty} \sum_{j=N}^{\infty} \mu(5B_j) = 0.$$

We claim that for all N

$$A \setminus \bigcup_{j=1}^N B_j \subset \bigcup_{j=N+1}^{\infty} 5B_j.$$

To prove this claim, fix $x \in A \setminus \bigcup_{j=1}^N B_j$. Choose $r > 0$ such that $B(x, r) \in \mathcal{B}$ and $B(x, r) \cap \bigcup_{i=1}^N B_i = \emptyset$. Such an r exists since balls in \mathcal{B} are closed. Now by choice of \mathcal{G} , $B(x, r)$ intersects some ball $B_j \in \mathcal{G}$ where $j \geq N+1$ with $\text{radius}(B_j) \geq 1/2r$. Thus $B(x, r) \subset 5B_j$. This proves the claim, and we conclude that $\mu(A \setminus \bigcup_{j=1}^{\infty} B_j) = 0$. \square

Next we will prove a lemma which relates the average value of the function f on balls centered on a set A to the measure of A . For $x \in H$ and $r > 0$ we define the average value of the function f on $B(x, r)$ by $\bar{f}_{B(x, r)} := \frac{1}{\mu(B(x, r))} \int_{B(x, r)} f d\mu$

Lemma 2.1.1. *Let μ be a pointwise doubling measure on a separable, infinite dimensional space H . Let $A \subset H$ be a bounded set such that for μ -a.e. $x \in A$*

$$\mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for all } r \in (0, 1],$$

and let $E \subset A$.

1. If $\liminf_{r \downarrow 0} \int_{B(x,r)} f d\mu \leq t$ for all $x \in E$ then $\int_E f d\mu \leq t\mu(A)$.

2. If $\limsup_{r \downarrow 0} \int_{B(x,r)} f d\mu \geq t$ for all $x \in E$ then $\int_E f d\mu \geq t\mu(A)$.

Proof. We present the proof of (1); the proof of (2) follows similarly. We assume without loss of generality that $\mu(E) < \infty$. Fix $\epsilon > 0$, and choose an open set U such that $E \subset U$ and $\mu(U) \leq \mu(E) + \epsilon$. For each $x \in E$, choose a sequence of radii $r_n = r_n(x)$ such that $r_n \leq 1$, $\lim_{n \rightarrow \infty} r_n = 0$, $B(x, r_n) \subset U$, and $\int_{B(x, r_n)} f d\mu < t + \epsilon$. Then $\mathcal{F} = \{B(x, r_n) : x \in E, n \in \mathbb{N}\}$ is a collection of balls that satisfies the assumptions of Theorem 2.1.3, so we choose disjoint balls $B_1, B_2, \dots \in \mathcal{B}$ with $\mu\left(E \setminus \bigcup_{j=1}^{\infty} B_j\right) = 0$. Then

$$\int_E f d\mu \leq \sum_j \int_{B_j} f d\mu < (t + \epsilon) \sum_j \mu(B_j) < (1 + \epsilon)\mu(U) \leq (t + \epsilon)(\mu(E) + \epsilon).$$

The second inequality follows from the assumption on the average value value integral. Letting $\epsilon \rightarrow 0$ we conclude our desired result. \square

Finally we prove a Lebesgue Differentiation Theorem which holds on sets where μ behaves like a doubling measures.

Theorem 2.1.4. *Let μ be a pointwise doubling measure on a separable infinite dimensional Hilbert space H . Let A be a bounded subset of H such that for μ -a.e. $x \in A$,*

$$\mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for } r \in (0, 1].$$

Let $f \in L_1(A, \mu)$. Then

$$\lim_{r \rightarrow 0} \int_{B(x,r)} f d\mu = f(x)$$

for μ -a.e. $x \in A$.

Proof. Define

$$E_{s,t} := \left\{ x \in A : \limsup_{r \rightarrow 0} \int_{B(x,r)} f d\mu \geq t > s \geq \liminf_{r \rightarrow 0} \int_{B(x,r)} f d\mu \right\},$$

and let

$$E^1 := \left\{ x \in A : \limsup_{r \rightarrow 0} \int_{B(x,r)} f d\mu \geq \liminf_{r \rightarrow 0} \int_{B(x,r)} f d\mu \right\}.$$

Note that $E^1 = \bigcup_{\substack{s,t \in \mathbb{Q} \\ s < t}} E_{s,t}$. By Lemma 2.1.1,

$$t\mu(E_{s,t}) \leq \int_{E_{s,t}} f d\mu \leq s\mu(E_{s,t}).$$

Since $t > s$, this implies that $\mu(E_{s,t}) = 0$. This holds for arbitrary $t > s$ so $\mu(E^1) = 0$. Next, define

$$E_M := \left\{ x \in A : \limsup_{r \rightarrow 0} \int_{B(x,r)} f d\mu \geq M \right\},$$

and let

$$E^2 := \left\{ x \in A : \limsup_{r \rightarrow 0} \int_{B(x,r)} f d\mu = \infty \right\}.$$

By Lemma 2.1.1 (2), we get that

$$\mu(E_M) \leq \frac{1}{M} \int_{E_M} f d\mu \leq \frac{1}{M} \int_A f d\mu.$$

It follows that $\lim_{M \rightarrow \infty} \mu(E_M) = 0$, and since $E^2 = \bigcap_{M \in \mathbb{N}} E_M$, $\mu(E^2) = 0$. Now

$$A \setminus (E^1 \cup E^2) = \left\{ x \in A : \lim_{r \rightarrow 0} \int_{B(x,r)} f d\mu \text{ exists and is finite} \right\}.$$

By the above estimations, $\mu(A) = \mu(A \setminus (E^1 \cup E^2))$ so we conclude that $\lim_{r \rightarrow 0} \int_{B(x,r)} f d\mu$ exists

and is finite for μ -a.e $x \in A$. □

Proof of Theorem 2.1.1. This result follows by Theorem 2.1.4 with $f = \chi_{A'}$. □

2.2 Hausdorff and Packing Measures

Although the goal of the dissertation is to characterize general pointwise doubling measures, we will rely on two specific families of measures, namely s -dimensional Hausdorff measures and s -dimensional packing measures, which we introduce here.

Definition 2.2.1 (s -dimensional Hausdorff measure). Let H be a separable infinite dimensional Hilbert space of \mathbb{R}^n , let $A \subset H$, and let $0 \leq s < \infty$. We define the s -dimensional *Hausdorff* measure \mathcal{H}^s so that

$$\mathcal{H}^s(A) = \lim_{\delta \downarrow 0} \mathcal{H}_\delta^s(A),$$

where

$$\mathcal{H}_\delta^s(A) = \inf \left\{ \sum_i \text{diam}(E_i)^s : A \subset \bigcup_i E_i, \text{diam}(E_i) \leq \delta \right\}.$$

For each set $A \subset H$ there exists a unique s such that $\mathcal{H}^t(A) = \infty$ for all $t < s$ and $\mathcal{H}^t(A) = 0$ for all $t > s$. This s is called the *Hausdorff dimension* of the set A . When we refer to the dimension of subsets of H in this dissertation, the term “dimension” can be understood to mean Hausdorff dimension.

Definition 2.2.2 (Lower Hausdorff density). Let $B(x, r) \subset H$ denote the closed ball with center $x \in H$ and radius $r > 0$. We define the *lower (Hausdorff) m -density* at x by

$$\underline{D}^m(\mu, x) := \liminf_{r \downarrow 0} \frac{\mu(B(x, r))}{r^m}.$$

The lower Hausdorff density provides one comparison of the behavior of the measure μ to the behavior of the m -dimensional Hausdorff measure.

Definition 2.2.3 (s -dimensional packing measure). Let H be a separable infinite dimensional Hilbert space or \mathbb{R}^n , let $A \subset H$, and let $0 \leq s < \infty$. For $0 < \delta < \infty$, set

$$P_\delta^s(A) = \sup \left\{ \sum_i \text{diam}(B_i)^s \right\}$$

where the supremum is taken over all disjoint families of closed balls $\{B_1, B_2, \dots\}$ centered on A such that $\text{diam}(B_i) \leq \delta$. Let $P^s(A) = \lim_{\delta \downarrow 0} P_\delta^s(A)$. Then the s -dimensional packing measure is defined to be

$$\mathcal{P}^s(A) = \inf \left\{ \sum_{i=1}^{\infty} P^s(A_i) : A = \bigcup_{i=1}^{\infty} A_i \right\}.$$

We will use the following two lemmas about packing measures.

Lemma 2.2.1. *Let $E \subset [0, 1]$. If $f : E \rightarrow H$ is L -Lipschitz then*

$$P^1(f(E)) \leq LP^1(E) \text{ and } \mathcal{P}^1(f(E)) \leq L\mathcal{P}^1(E).$$

Proof. Assume $P^1(E) < \infty$ and that $f : E \rightarrow H$ is L -Lipschitz. Given $\epsilon > 0$, pick $\eta > 0$ so that $P_\eta^1(E) \leq P^1(E) + \epsilon$. Fix $0 < \delta \leq L\eta$, and let $\{B_H(f(x_i), r_i) : i \geq 1\}$ be an arbitrary disjoint collection of balls in H centered in $f(E)$ such that $2r_i \leq \delta$ for all $i \geq 1$. Since f is L -Lipschitz,

$$f(B_{\mathbb{R}}(x_i, r_i/L)) \subset B_H(f(x_i), r_i) \text{ for all } i \geq 1.$$

Thus $\{B_{\mathbb{R}}(x_i, r_i/L) : i \geq 1\}$ is a disjoint collection of balls in \mathbb{R} centered in E such that

$$2r_i/L \leq \delta/L \leq \eta.$$

Hence

$$\sum_{i=1}^{\infty} (2r_i) = L \sum_{i=1}^{\infty} (2r_i/L) \leq L \cdot P_{\eta}^1(E) \leq L(P^1(E) + \epsilon).$$

Taking the supremum over all δ packings of $f(E)$ we obtain $P_{\delta}^1(f(E)) \leq L(P^1(E) + \epsilon)$. The corresponding inequality for packing measure $\mathcal{P}^1(E)$ follows immediately. \square

Lemma 2.2.2. *Let $A \subset H$ be a bounded set, and suppose that there exists $r_0 > 0$ and $M < \infty$ such that for every $x \in A$ and $0 < r \leq r_0$*

$$\mu(B(x, 2r)) \leq M\mu(B(x, r)) \text{ and } \underline{D}^1(\mu, x) \leq \lambda.$$

Then

$$\mu(A) \leq \lambda \mathcal{P}^1(A).$$

Proof. Let $E \subset A$ and $\epsilon > 0$. By definition of packing measure, choose $\delta > 0$ such that $P_{\delta}^1(E) \leq P^1(E) + \epsilon$. Using the bounded lower density assumption on μ , for each $x \in E$ we can choose a sequence $\{r_{x,i}\}_{i=1}^{\infty}$ satisfying $r_{x,i} \leq \min\{\delta, r_0/8\}$, $r_{x,i} \rightarrow 0$ as $i \rightarrow \infty$, and

$$\mu(B(x, r_{x,i})) \leq 2\lambda r_{x,i} \text{ for each } i.$$

Let $\mathcal{F} = \{B(x, r_{x,i}) : x \in E\}$ where B is a closed ball. By Theorem 2.1.3 we can choose a disjoint countable subcollection $\mathcal{G} \subset \mathcal{F}$ such that

$$\mu\left(E \setminus \bigcup_{B_i \in \mathcal{G}} B_i\right) = 0.$$

Then

$$\mu(E) \leq \sum_{B_i \in \mathcal{G}} \mu(B_i) \leq \sum_{B_i \in \mathcal{G}} \lambda 2r_{B_i} \leq P_{\delta}^1(E) \leq \lambda(P^1(E) + \epsilon).$$

Let $\epsilon \downarrow 0$ to conclude $\mu(E) \leq \lambda P^1(E)$ for $E \subset A$. Thus, for $A = \bigcup_{l=1}^{\infty} E_l$,

$$\mu(A) \leq \sum_{l=1}^{\infty} \mu(E_l) \leq \lambda \sum_{l=1}^{\infty} P^1(E_l),$$

and $\mu(A) \leq \lambda P^1(A)$. □

2.3 Finite overlap property

To make several counting arguments in this dissertation, we will need to quantify the overlap of balls.

Definition 2.3.1 (Finite overlap). We say a subcollection $\mathcal{C}' \subset \mathcal{C}^\mu$ satisfies the *finite overlap condition* with respect to μ if for each $j \geq k$ there exists a constant $P(\mathcal{C}', j - k)$ such that for any ball $B = B(x, \lambda_2 2^{-k}) \in \mathcal{C}'$ there exist at most $P(\mathcal{C}', j - k)$ balls $B' = B(y, \lambda_2 2^{-j}) \in \mathcal{C}'$ satisfying $\mu(B \cap B') > 0$.

Lemma 2.3.1. *Let μ be a D -doubling measure, and let \mathcal{C}^μ be the multiresolution family of balls constructed using the support of μ as the carrying set. Then \mathcal{C}^μ satisfies the finite overlap condition.*

Proof. Let $j \geq k$, set $B = B(x, \lambda_2 2^{-k})$ and $B' = B(y, \lambda_2 2^{-j})$, and suppose that $B \cap B' \neq \emptyset$. For arbitrary $z \in B'$,

$$\text{dist}(z, x) \leq \text{dist}(z, y) + \text{dist}(y, x) \leq 2\lambda_2 2^{-k}. \quad (2.3.1)$$

In particular, $B' \subset 2B$. Furthermore, for $z \in 2B$,

$$\text{dist}(z, y) \leq \text{dist}(z, x) + \text{dist}(x, y) \leq 2\lambda_2 2^{-k} + \lambda_2 2^{-j} < 4\lambda_2 2^{-k}, \quad (2.3.2)$$

so $2B \subset 4 \cdot 2^{j-k} B'$.

Now let C denote $\#\{B'_i \in \mathcal{C}_j^\mu : \mu(B'_i \cap B) > 0\}$. Since $\mu(B'_i \cap B) > 0$ implies that $B'_i \cap B \neq \emptyset$, we use (2.3.1) and (2.3.2) to estimate

$$\begin{aligned} \mu(2B) &\geq \mu\left(\bigcup_{i=1}^C B'_i\right) \geq \mu\left(\bigcup_{i=1}^C \frac{1}{2\lambda_2} B'_i\right) = \sum_{i=1}^C \mu\left(\frac{1}{2\lambda_2} B'_i\right) \geq \sum_{i=1}^C D^{-(j-k+3+\log(\lambda_2))} \mu(4 \cdot 2^{j-k} B'_i) \\ &\geq C \cdot D^{-(j-k+3+\log(\lambda_2))} \mu(2B). \end{aligned}$$

This implies $D^{j-k+3+\log(\lambda_2)} \geq C$. Thus we may take the finite overlap constant to be $P(\mathcal{C}', j-k) := D^{j-k+2+\log(\lambda_2)}$. \square

Chapter 3

Rectifiable measures

3.1 Necessary Condition

The goal of this section is to prove the necessary direction of Theorem A. Throughout we let H denote a separable, finite or infinite dimensional Hilbert space. We begin with a theorem about finite measures that satisfy the finite overlap property.

Theorem 3.1.1. *Let ν be a finite Borel measure on H whose support is contained in the support of μ . Let Γ be a rectifiable curve, and let $E \subset \Gamma$ such that $\nu(B(x, r)) \geq dr$ for all $x \in E$ and for all $0 < r \leq r_0$. Additionally, suppose that $\mathcal{C}^\nu = \{B \in \mathcal{C}^\mu : \nu(B \cap E) > 0\}$ satisfies the finite overlap property with constants $P(\mathcal{C}^\nu, j - k)$ for $j \geq k$. Then*

$$\sum_{B \in \bigcup_{k=l}^{\infty} \mathcal{C}_k^\mu} \beta_2(\nu, 2B)^2 \frac{\text{diam}(B)}{\nu(B)} \int_E \chi_B(x) d\nu \lesssim \mathcal{H}^1(\Gamma) + \nu(H \setminus \Gamma)$$

where $l \geq 0$ is the smallest non-negative integer such that $2^{-l} \leq r_0$. Here the implied constants depend only on d and $P(\mathcal{C}^\nu, j - k)$.

To prove Theorem 3.1.1, we will use a measure-theoretic result for weighted sums.

Lemma 3.1.1. *Suppose that $E_0 \supset \cdots \supset E_k \supset E_{k+1} \supset \cdots$ and $E = \bigcap_{k=0}^{\infty} E_k$. Additionally suppose $\nu(E_0) < \infty$, $\omega : E_0 \rightarrow [0, \infty)$, $\omega = 0$ on E , $c_k \geq 0$, and $\sum_{k=0}^j c_k \sup_{x \in E_j} \omega(x) \leq C < \infty$. Then*

$$\sum_{k=0}^{\infty} c_k \int_{E_k} \omega(x) d\nu(x) = \sum_{j=0}^{\infty} \sum_{k=0}^j c_k \int_{E_j \setminus E_{j+1}} \omega(x) d\nu(x) \leq C \mu(E_0 \setminus E).$$

Proof. First note that for each k ,

$$\int_{E_k} \omega(x) d\nu = \sum_{j=k}^{\infty} \int_{E_j \setminus E_{j+1}} \omega(x) d\nu.$$

Therefore,

$$\begin{aligned} \sum_{k=0}^{\infty} c_k \int_{E_k} \omega(x) d\nu &= \sum_{k=0}^{\infty} c_k \sum_{j=k}^{\infty} \int_{E_j \setminus E_{j+1}} \omega(x) d\nu = \sum_{j=0}^{\infty} \sum_{k=1}^j c_k \int_{E_j \setminus E_{j+1}} \omega(x) d\nu \\ &= \sum_{j=0}^{\infty} \int_{E_j \setminus E_{j+1}} \sum_{k=1}^j c_k \omega(x) d\nu \leq \sum_{j=1}^{\infty} \int_{E_j \setminus E_{j+1}} C d\nu \\ &= \sum_{j=1}^{\infty} C \mu(E_j \setminus E_{j+1}) \leq C \mu(E_0 \setminus E). \end{aligned} \quad \square$$

We now return to the proof of Theorem 3.1.1.

Proof. Let Γ be a rectifiable curve as specified above. We partition \mathcal{C}^μ into three subsets:

$$\mathcal{C}_\emptyset^\mu = \{B : \nu(B \cap E) = 0\},$$

$$\mathcal{C}_\Gamma^\mu = \left\{ B \in \bigcup_{k=l}^{\infty} \mathcal{C}_k^\mu : \nu(B \cap E) > 0 \text{ and } \epsilon \beta_2(\nu, 2B) \leq \beta_\Gamma(\lambda_3 B) \right\},$$

$$\mathcal{C}_\nu^\mu = \left\{ B \in \bigcup_{k=l}^{\infty} \mathcal{C}_k^\mu : \nu(B \cap E) > 0 \text{ and } \beta_\Gamma(\lambda_3 B) < \epsilon \beta_2(\nu, 2B) \right\},$$

where restrictions on $\lambda_3 > 0$ and $\epsilon > 0$ will be specified later. Note that \mathcal{C}_Γ^μ and \mathcal{C}_ν^μ are subsets of \mathcal{C}^ν , and hence satisfy the finite overlap property with the same overlap constants as \mathcal{C}^ν . Now

$$\begin{aligned} \sum_{B \in \bigcup_{k=l}^{\infty} \mathcal{C}_k^\mu} \beta_2(\nu, 2B)^2 \frac{\text{diam } B}{\nu(B)} \int_E \chi_B(x) d\nu &= \sum_{B \in \bigcup_{k=l}^{\infty} \mathcal{C}_k^\mu} \beta_2(\nu, 2B)^2 \text{diam } B \frac{\nu(E \cap B)}{\nu(B)} \\ &\leq \underbrace{\epsilon^{-2} \sum_{B \in \mathcal{C}_\Gamma^\mu} \beta_\Gamma(\lambda_3 B)^2 \text{diam } B}_I + \underbrace{\sum_{B \in \mathcal{C}_\nu^\mu} \beta_2(\nu, 2B)^2 \text{diam } B}_{II}. \end{aligned}$$

We estimate the sums I and II separately. To estimate I we will invoke Theorem 1.2.1, the Analyst's Traveling Salesman Theorem for sets in Hilbert space. In order to apply the theorem, we first need to translate from balls centered on the carrying set X to balls centers on the rectifiable curve Γ . In doing so, we aim to establish the following bound:

$$\sum_{B \in \mathcal{C}_\Gamma^\mu \cap \mathcal{C}_k^\mu} \beta_\Gamma(\lambda_3 B)^2 \text{diam } B \leq C \sum_{U \in \mathcal{G}_k^\Gamma} \beta_\Gamma(U)^2 \text{diam } U \quad (3.1.1)$$

where $k \geq l$, the constant C is independent of k , and \mathcal{G}_k^Γ is a multiresolution family of balls for the rectifiable curve Γ . The dilation factor λ_1 for balls in \mathcal{G}_k^Γ will be specified below. To show that (3.1.1) holds, fix $B \in \mathcal{C}_k^\mu$, and let x_B denote the center point. Since $\nu(B \cap \Gamma) \geq \nu(B \cap E) > 0$, we may choose $g \in B \cap \Gamma$ and $n_B \in N_k$ such that $\text{dist}(g, n_B) \leq 2^{-k}$. Now for $y \in \lambda_3 B$,

$$\text{dist}(y, n_B) \leq \text{dist}(y, x_B) + \text{dist}(x_B, g) + \text{dist}(g, n_B) \leq \lambda_3(\lambda_2 2^{-k}) + \lambda_2 2^{-k} + 2^{-k} < 3\lambda_3 \lambda_2 2^{-k}.$$

Thus, by requiring $\lambda_1 \geq 3\lambda_3 \lambda_2$, we have $\lambda_3 B \subset U = B(n_B, \lambda_1 2^{-k})$. As a consequence, we can

control $\beta_\Gamma(\lambda_3 B)$ with $\beta_\Gamma(U)$. In particular, there is a line ℓ_U such that

$$\beta_\Gamma(U) \geq \frac{1}{2} \sup_{y \in U \cap \Gamma} \left(\frac{\text{dist}(y, \ell_U)}{\text{diam}(U)} \right) \geq \frac{1}{2} \sup_{y \in \lambda_3 B \cap \Gamma} \left(\frac{\text{dist}(y, \ell_U)}{\text{diam}(\lambda_3 B)} \right) \left(\frac{\text{diam}(\lambda_3 B)}{\text{diam}(U)} \right) \geq \frac{\lambda_3 \lambda_2}{2\lambda_1} \beta_\Gamma(\lambda_3 B).$$

It remains to show that we can control the number of balls in \mathcal{C}_k^μ assigned to each by $U \in \mathcal{G}_k^\Gamma$. To this end, fix a ball $U \in \mathcal{G}_k^\Gamma$. We claim that there are at most $P\left(\mathcal{C}^\nu, \lceil \log \frac{2\lambda_1}{\lambda_2} \rceil\right)$ balls $B' \in \mathcal{C}_k^\mu$ contained in U . Note that if no balls are contained in U then the bound holds trivially. Otherwise, fix $B \subset U$. It follows from triangle inequality that $U \subset 2^{\lceil \log(2\lambda_1/\lambda_2) \rceil} B$. By the finite overlap property there are at most $P\left(\mathcal{C}^\nu, \lceil \log \frac{2\lambda_1}{\lambda_2} \rceil\right)$ balls $B' \in \mathcal{C}_k^\mu$ such that $\mu(B' \cap 2^{\lceil \log(2\lambda_1/\lambda_2) \rceil} B) > 0$, and so there are at most $P\left(\mathcal{C}^\nu, \lceil \log \frac{2\lambda_1}{\lambda_2} \rceil\right)$ balls $B' \subset U$. This establishes inequality (3.1.1) for each $k \geq l$. Now summing over all generations k and applying Theorem 1.2.1 (1) we conclude that

$$\sum_{B \in \mathcal{C}_\Gamma^\mu} \beta_\Gamma(\lambda_3 B) \text{diam}(B) \leq \frac{P\left(\mathcal{C}^\nu, \lceil \log \frac{2\lambda_1}{\lambda_2} \rceil\right) \lambda_3 \lambda_2}{2\lambda_1} \sum_{U \in \mathcal{G}^\Gamma} \beta_\Gamma(U) \text{diam}(U) \lesssim \mathcal{H}^1(\Gamma)$$

where the symbol \lesssim depends on λ_2, λ_3 , and $P\left(\mathcal{C}^\nu, \lceil \log \frac{2\lambda_1}{\lambda_2} \rceil\right)$. This completes the estimate of sum I .

We now begin the estimation of II . For $B \in \mathcal{C}_\nu^\mu \cap \mathcal{C}_k^\mu$, we fix a line $\ell = \ell_B \in H$ satisfying

$$\begin{aligned} \sup_{z \in \Gamma \cap \lambda_3 B} \text{dist}(z, \ell) &\leq 2\beta_\Gamma(\lambda_3 B) \text{diam}(\lambda_3 B) \\ &< 2\epsilon\beta_2(\nu, 2B) \text{diam}(\lambda_3 B) \\ &= 2\lambda_3\epsilon\beta_2(\nu, 2B) \text{diam}(B). \end{aligned}$$

The first inequality follows from definition of $\beta_\Gamma(\lambda_3 B)$; the second inequality follows from definition of \mathcal{C}_ν^μ . We partition $2B$ into a set of points near the line ℓ and a set of points far from the line

ℓ :

$$N(B) = \{x \in 2B : \text{dist}(x, \ell) \leq 2\lambda_3\epsilon\beta_2(\nu, 2B) \text{diam}(B)\},$$

$$F(B) = \{x \in 2B : \text{dist}(x, \ell) > 2\lambda_3\epsilon\beta_2(\nu, 2B) \text{diam}(B)\}.$$

Using this partition of the ball $2B$, we see that

$$\begin{aligned} \beta_2(\nu, 2B)^2 &\leq \int_N \left(\frac{\text{dist}(x, \ell)}{\text{diam } 2B} \right)^2 \frac{d\nu(x)}{\nu(2B)} + \int_F \left(\frac{\text{dist}(x, \ell)}{\text{diam } 2B} \right)^2 \frac{d\nu(x)}{\nu(2B)} \\ &\leq \lambda_3^2 \epsilon^2 \beta_2(\nu, 2B)^2 + \int_F \left(\frac{\text{dist}(x, \ell)}{\text{diam}(2B)} \right)^2 \frac{d\nu(x)}{\nu(2B)} \\ &\leq 3\lambda_3^2 \epsilon^2 \beta_2(\nu, 2B)^2 + \int_F \left(\frac{\text{dist}(x, \Gamma \cap \lambda_3 B)}{\text{diam}(2B)} \right)^2 \frac{d\nu(x)}{\nu(2B)}, \end{aligned}$$

where last inequality follows since

$$\begin{aligned} \left(\frac{\text{dist}(x, \ell)}{\text{diam } 2B} \right)^2 &\leq \left(\frac{\text{dist}(x, \Gamma \cap \lambda_3 B)}{\text{diam } 2B} + \frac{\text{dist}(\Gamma \cap \lambda_3 B, \ell)}{\text{diam } 2B} \right)^2 \\ &\leq 2 \left(\frac{\text{dist}(x, \Gamma \cap \lambda_3 B)}{\text{diam } 2B} \right)^2 + 2 \left(\frac{\text{dist}(\Gamma \cap \lambda_3 B, \ell)}{\text{diam } 2B} \right)^2 \\ &\leq 2 \left(\frac{\text{dist}(x, \Gamma \cap \lambda_3 B)}{\text{diam } 2B} \right)^2 + 2\lambda_3^2 \epsilon^2 \beta_2(\nu, 2B)^2. \end{aligned}$$

The choice of ℓ is used to go between the second and third lines. Now since $F \subset 2B$, $\text{dist}(x, \Gamma) \leq \text{diam } 2B = 4\lambda_2 2^{-k}$. Therefore, if we fix $\lambda_3 \geq 6\lambda_2$, then

$$\text{dist}(x, \Gamma \cap \lambda_3 B) = \text{dist}(x, \Gamma).$$

To see this explicitly, let $z \in 2B$ and choose z_Γ to be a closest point in Γ to z . Then

$$\text{dist}(z_\Gamma, x_B) \leq \text{dist}(z_\Gamma, z) + \text{dist}(z, x_B) \leq 4\lambda_2 2^{-k} + \lambda_2 2^{-k} < 6\lambda_2 2^{-k}.$$

Once λ_3 is fixed, choose ϵ small enough to guarantee that $3\lambda_3^2\epsilon^2 < \frac{1}{2}$. Then we have that

$$\beta_2(\nu, 2B)^2 \leq 2 \int_F \left(\frac{\text{dist}(x, \Gamma)}{\text{diam } 2B} \right)^2 \frac{d\mu(x)}{\mu(2B)}.$$

To prove that II is finite, it suffices to show that

$$\sum_{B \in \mathcal{C}_\nu^\mu} \int_F \left(\frac{\text{dist}(x, \Gamma)}{\text{diam } 2B} \right)^2 \frac{d\mu(x)}{\mu(2B)} \text{diam}(B) < \infty.$$

This sum is an improvement over the original in that, unlike the lines ℓ_B , Γ is a fixed reference set which is independent of the window B . Now observe that for $B \in \mathcal{C}_\nu^\mu$ there exists $y \in E \cap B$. For arbitrary $z \in B(y, 2^{-k})$, an application of the triangle inequality yields

$$\text{dist}(z, x_B) \leq \text{dist}(z, y) + \text{dist}(y, x_B) \leq 2\lambda_2 2^{-k},$$

which implies that $B(y, 2^{-k}) \subset 2B$. By the lower regularity assumption on points in E ,

$$\mu(2B) \geq \mu(B(y, 2^{-k})) \geq d2^{-k} = \frac{d}{2\lambda_2} \text{diam}(B),$$

and, in particular,

$$\frac{2\lambda_2}{d} \geq \frac{\text{diam}(B)}{\mu(2B)}.$$

Using this density estimate, we conclude that

$$\begin{aligned} \sum_{B \in \mathcal{C}_\nu^\mu} \int_F \left(\frac{\text{dist}(x, \Gamma)}{\text{diam}(2B)} \right)^2 \frac{d\mu(x)}{\mu(2B)} \text{diam } B &\leq \frac{2\lambda_2}{d} \sum_{B \in \mathcal{C}_\nu^\mu} \int_{2B} \left(\frac{\text{dist}(x, \Gamma)}{\text{diam}(2B)} \right)^2 d\mu(x) \\ &\leq \frac{2\lambda_2}{d} \sum_{B \in \mathcal{C}_\nu^\mu} \frac{1}{(\text{diam}(2B))^2} \int_{2B} \text{dist}^2(x, \Gamma) d\mu(x) \end{aligned}$$

$$\begin{aligned}
&\leq \frac{2\lambda_2}{d} \sum_{k=l}^{\infty} \sum_{B \in \mathcal{C}_k^\mu} \frac{4^k}{16\lambda_2^2} \int_{2B} \text{dist}^2(x, \Gamma) d\mu(x) \\
&\leq \frac{2}{d} \sum_{k=l}^{\infty} \frac{4^{k-2}}{\lambda_2} P(\mathcal{C}^\nu, 0) \int_{2B} \text{dist}^2(x, \Gamma) d\mu(x).
\end{aligned}$$

Here the finite overlap factor $P(\mathcal{C}^\nu, 0)$ accounts for potential overlapping of ball in \mathcal{C}_k^μ . Set $E_k := \bigcup_{B \in \mathcal{C}_k^\mu} 2B$, $c_k = 4^{k-2}$, and $\omega(x) = \text{dist}^2(x, \Gamma)$. Then

$$\sum_{k=l}^j 4^{k-2} \sup_{x \in E_j} \omega(x) \leq \sum_{k=l}^{\infty} 4^{k-2} (2^{-j+1})^2 = \sum_{k=l}^j 4^{k+j-1} < \sum_{j=l}^{\infty} 4^{-j-1} < \frac{4^{-l}}{3}.$$

Furthermore, we verify that $E_{k+1} \subset E_k$ for each k . Let $z \in E_{k+1}$, and let $B_z = B(x_z, 2\lambda_2 2^{-(k+1)})$ denote a ball in \mathcal{C}_k^μ that contains z . By maximality of X_k^μ , there is $y_z \in X_k^\mu$ such that

$$\text{dist}(z, y_z) \leq \text{dist}(z, x_z) + \text{dist}(x_z, y_z) \leq 2\lambda_2 2^{-(k+1)} + 2^{-k} < 2\lambda_2 2^{-k}.$$

This implies that $z \in B(y_z, 2\lambda_2 2^{-k})$ and it fact that $B(x_z, 2\lambda_2 2^{-(k+1)}) \subset B(y_z, 2\lambda_2 2^{-k})$. Of course by definition of \mathcal{C}_k^μ , $B(y_z, 2\lambda_2 2^{-k}) \subset E_k$, so we conclude that $E_{k+1} \subset E_k$. Thus we may employ the following Lemma 3.1.1 to conclude that

$$\sum_{B \in \mathcal{C}_2^\mu} \int_F \left(\frac{\text{dist}(x, \Gamma)}{\text{diam } 2B} \right)^2 \frac{d\mu(x)}{\mu(2B)} \text{diam}(2B) \leq C(d, \lambda_2, P_0) \nu(H \setminus \Gamma).$$

Note, in particular that C is independent of Γ . Combining our estimates of I and II , we get the estimate

$$\sum_{B \in \bigcup_{k=l}^{\infty} \mathcal{C}_k^\mu} \beta_2^2(\nu, 2B) \frac{\text{diam}(B)}{\nu(B)} \int_E \chi_B(x) d\nu \lesssim \mathcal{H}^1(\Gamma) + \nu(H \setminus \Gamma).$$

In particular, since Γ is a rectifiable curve and ν is a finite measure, we conclude that the sum is

finite. □

Definition 3.1.1 (Lower Ahlfors regular). We say a set E is *lower d -Ahlfors regular* with respect to the measure μ if

$$\mu(B(x, r)) \geq dr \text{ for every } x \in E \text{ and } 0 < r \leq \text{diam } E.$$

We say a measure μ is *lower d -Ahlfors regular* if there exists a lower d -Ahlfors regular set that carries μ .

Corollary 3.1.1. *Let μ be a finite, lower Ahlfors d -regular Borel measure on H . Suppose that μ is D -doubling. Then*

$$\int_{\Gamma} \hat{J}_2(\mu, x) d\mu(x) < \mathcal{H}^1(\Gamma) + \mu(H \setminus \Gamma) < \infty.$$

Proof. Recall by Theorem 2.3.1 that since μ is doubling we can construct \mathcal{C}^μ to satisfy the finite overlap property. Then this result follows immediately from Theorem 3.1.1 by setting $\nu = \mu$ and observing that

$$\int_{\Gamma} \hat{J}_2(\mu, x) d\mu(x) = \sum_{B \in \bigcup_{k=1}^{\infty} \mathcal{C}_k^\mu} \beta_2^2(\mu, 2B) \frac{\text{diam}(B)}{\mu(B)} \int_{\Gamma} \chi_{2B}(x) d\mu(x). \quad \square$$

We will next show that points of zero lower Hausdorff density do not see rectifiable curves. This will allow us to focus on points with positive lower density for the proof of the necessary condition of Theorem A.

Theorem 3.1.2. *If μ is a pointwise doubling measure on H then $\mu \llcorner \{x \in H : \underline{D}^1(\mu, x) = 0\}$ is purely unrectifiable.*

The outline of the proof of this theorem follows similarly to that of [7, Theorem 2.7]. However,

we include details to make explicit the use of the pointwise doubling property in the Hilbert space setting.

Proof. Let μ is a pointwise doubling measure on H , and suppose that μ is rectifiable. Set $A = \{x \in X : \underline{D}^1(\mu, x) = 0\}$. We will show that A intersects the image of every Lipschitz map on a set of measure zero, and hence A itself has zero measure. Let $f : [0, 1] \rightarrow H$ be L -Lipschitz. By Lemma 2.2.1, for any $E \subset [0, 1]$, $\mathcal{P}^1(f(E)) \leq L\mathcal{P}^1(E) < \infty$. Set

$$(A \cap f(E))_j^D := \{x \in A \cap f(E) : \mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for all } 0 < r \leq 1/j\}.$$

By the pointwise doubling assumption on μ ,

$$\bigcup_{D=1}^{\infty} \bigcup_{j=1}^{\infty} (A \cap f(E))_j^D = A \cap f(E).$$

Fix some D and j . Since E is bounded and f is continuous, $(A \cap f(E))_j^D$ is bounded. Now fix some $\lambda > 0$, and recall that $\underline{D}^1(\mu, x) = 0 \leq \lambda$ for all $x \in A$ and, in particular, for all $x \in (A \cap f(E))_j^M$.

By Lemma 2.2.2, we have that

$$\mu((A \cap f(E))_j^D) \leq \lambda \mathcal{P}^1((A \cap f(E))_j^D) < \infty.$$

Thus, letting $\lambda \rightarrow 0$, $\mu((A \cap f(E))_j^D) = 0$ for every $E \subset [0, 1]$ and every Lipschitz function f . Hence $\mu((A \cap f(E))) = 0$ for every $E \subset [0, 1]$ and every Lipschitz function f . Since μ is rectifiable, we conclude that $\mu(A) = 0$. It follows immediately that for a rectifiable measure μ , $\underline{D}^1(\mu, x) > 0$ for μ -a.e. $x \in H$, and conversely that $\mu \llcorner \{x : \underline{D}^1(\mu, x) = 0\}$ is purely unrectifiable. \square

With Theorem 3.1.2 established, it remains to prove the following theorem in order to obtain

the necessary condition of Theorem A.

Theorem 3.1.3. *Let μ be a pointwise doubling measure on a separable, infinite dimensional Hilbert space H . If μ is rectifiable then*

$$\hat{J}_2(\mu, x) < \infty \text{ for } \mu\text{-a.e. } x \in H.$$

Proof. Let μ a rectifiable pointwise doubling measure on H . Since μ is rectifiable, choose a countable family $\{\Gamma_i\}_{i=1}^\infty$ of rectifiable curves to which μ gives full mass, i.e., $\mu(H \setminus \bigcup_{i=1}^\infty \Gamma_i) = 0$. As a consequence of Theorem 3.1.2, μ has positive lower density μ -a.e.. This, together with the pointwise doubling property, implies that μ gives full mass to $\bigcup_{D=1}^\infty \bigcup_{m=1}^\infty \bigcup_{n=1}^\infty E_{m,n}^D$ where

$$E_{m,n}^D = \{x \in H : \mu(B(x, r)) \geq 2^{-m}r \text{ and } \mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for all } r \in (0, 2^{-n}]\}.$$

Therefore, to establish the necessary direction of Theorem A, it suffices to show that $\hat{J}_2(\mu, x) < \infty$ at μ -a.e. $x \in \Gamma_i \cap E_{m,n}^D$ for every i, m, n , and D . To this end, fix i, m, n , and D . Set $\Gamma = \Gamma_i$ and then set $E = \Gamma \cap E_{m,n}^D$. Define

$$\mathcal{C}_E^\mu := \{B \in \mathcal{C}^\mu : \mu(E \cap B) > 0 \text{ and } \text{radius}(B) \leq \lambda_2 2^{-(n+3)}\},$$

We'll show that \mathcal{C}_E^μ satisfies the finite overlap property. Let $B \in \mathcal{C}_E^\mu \cap \mathcal{C}_k^\mu$ for some $k \geq n + 3$. Let $\{B_i\}_{i=1}^c$ be the collection of balls in $\mathcal{C}_E^\mu \cap \mathcal{C}_j^\mu$, $j \geq k$, that intersect B . Then

$$\begin{aligned} \mu(4B) &\geq \mu\left(\bigcup_{i=1}^c 2B_i\right) \geq \mu\left(\bigcup_{i=1}^c B(e_i, \lambda_2 2^{-(j+1)})\right) \geq D^{-N_{j-k}} \sum_{i=1}^c \mu\left(B(e_i, 2^{N_{j-k}} \lambda_2 2^{-(j+1)})\right) \\ &\geq D^{-N_{j-k}} c\mu(4B). \end{aligned}$$

Here N_{j-k} is the maximum number of times the ball $B(e_i, 2^{-(j+1)})$, a ball centered at a point in E and contained in $2B_i$, must be doubled to guarantee that the dilated ball contains $\mu(4B)$. Note that N_{k-j} is dependent only on the difference between j and k . We conclude that $c \leq D^{N_{j-k}}$, so we may take $P(\mathcal{C}_E^\mu, j-k) = D^{N_{j-k}}$. Now define the measure ν by

$$\nu := \mu \llcorner \bigcup_{\mathcal{C}_E^\mu} 2B.$$

Of course Γ has finite length, and we have $E \subset B(x, \text{length}(\Gamma))$ for any $x \in E$. It follows that ν has bounded support and hence, by our definition of pointwise doubling measures, ν is finite. Thus

$$\begin{aligned} \sum_{B \in \bigcup_{k=n+3}^\infty \mathcal{C}_k^\mu} \beta_2(\mu, 2B)^2 \frac{\text{diam } B}{\mu(B)} \int_E \chi_B(x) d\mu(x) &= \sum_{B \in \mathcal{C}_E^\mu} \beta_2(\nu, 2B)^2 \frac{\text{diam } B}{\nu(B)} \int_E \chi_B(x) d\nu(x) \\ &\lesssim \mathcal{H}^1(\Gamma) + \nu(H \setminus \Gamma) < \infty \end{aligned}$$

where the last inequality follows from Theorem 3.1.1. Then the positive lower density assumption on μ together with the finiteness of μ on bounded sets guarantees that there are at most finitely many balls in $\bigcup_{k=1}^{n+2} \mathcal{C}_k^\mu$ that contain x . Thus,

$$\int_E \hat{J}_2(\mu, x) d\mu(x) = \sum_{B \in \bigcup_{k=1}^\infty \mathcal{C}_k^\mu} \beta_2(\mu, 2B)^2 \frac{\text{diam } B}{\mu(B)} \int_E \chi_B(x) d\mu(x) < \infty.$$

Letting i, m, n , and D vary over all natural numbers proves the result. \square

3.2 Sufficient condition for rectifiability

In this section we prove the sufficient condition of Theorem A. As mentioned in the introduction, the main machinery for this proof is Theorem C which is proved in sections 4.1-4.3. In order to establish a setting in which we can apply Theorem C, we begin this section by defining a tree structure on \mathcal{C}^μ .

We define the tree structure on the collection \mathcal{C}^μ to model the natural nesting structure of dyadic cubes in Euclidean space. The tree structure here is more complex than the structure for the dyadic cubes, where we can track the lineage of cubes from an initial generation, say cubes of side-length 1. This is because, for a fixed generation of net points X_k^μ , we cannot in general choose a dilation of balls centered at the net points such that the balls are simultaneously pairwise disjoint and also covering H . To define the family structure, we rely on the following lemma.

Lemma 3.2.1 ([30, Lemma 3.19]). *Given $c \leq \frac{1}{4\lambda_2}$ and $J \geq 10$, there exist J families of connected sets in H such that (denoting a single family by $\{Q_k^j\}_{k=k_0, j=0}^{k=\infty, j=j_n}$):*

- (i) *For every $x \in X_k^\mu$ there exists a unique j such that for $B_k^j \in \mathcal{C}^\mu$, $cB_k^j \subset Q_k^j$ for some family where $\text{radius}(B_k^j) = \lambda_2 2^{-k}$.*
- (ii) $2c\lambda_2 2^{-k} \leq \text{diam } Q_k^j \leq 2(1 + 4 \cdot 2^{-J+1})c\lambda_2 2^{-k}$
- (iii) *If $j \neq j'$ then $Q_k^j \cap Q_k^{j'} = \emptyset$ as long as Q_k^j and $Q_k^{j'}$ belong to the same family. In this case, $\text{dist}(Q_k^j, Q_k^{j'}) \geq 2^{-k-1}$,*
- (iv) *If $Q_k^j \cap Q_l^{j'} \neq \emptyset$ for $l > k$ and Q_k^j and $Q_l^{j'}$ belong to the same family then $Q_l^{j'} \subset Q_k^j$.*

We call the set Q_k^j satisfying properties (i)-(iv) the *core* of the ball $B_k^j \in \mathcal{C}^\mu$. The core Q_k^j can be defined in the following way. Fix k , and choose $B_k^j \in \mathcal{C}_k^\mu$. If $j \neq j'$ then $\text{dist}(cB_k^j, cB_k^{j'}) > 2^{-(k+1)}$

by choice of the net X_k^μ . Set

$$\begin{aligned} Q_{k,0}^j &:= cB_k^j, \\ Q_{k,i+1}^j &:= Q_{k,i}^j \cup \bigcup_{cB_{k+(i+1)J}^{j'} \cap Q_{k,i}^j \neq \emptyset} cB_{k+(i+1)J}^{j'}, \\ Q_k^j &:= \lim_{i \rightarrow \infty} Q_{k,i}^j. \end{aligned}$$

Then we define the k^{th} family of cores to be $\mathcal{Q}_k := \{Q_{k+iJ}^j : i \in \mathbb{N}\}$, and we denote the collection of all cores by $\mathcal{Q} := \bigcup_{k=k_0}^\infty \mathcal{Q}_k$. We remark that the construction of these cores depends on the choices of the constant c and J . For balls that belong to the same family there are intrinsic tree structures given by inclusion. We use the tree structures on \mathcal{Q}_k to define a tree structure on the balls in \mathcal{C}^μ . In particular,

- for $l = k + J$, if $Q_k^j \cap Q_l^{j'} \neq \emptyset$ then $Q_l^{j'} \subset Q_k^j$, and we say that $B_l^{j'}$ is a *child* of B_k^j ($B_k^j \succ B_l^{j'}$);
- for $k = l - J$, if there exists j such that $Q_k^j \cap Q_l^{j'} \neq \emptyset$ then $Q_k^j \supset Q_l^{j'}$, and we say that B_k^j is the *parent* of $B_l^{j'}$, $(B_l^{j'})^\uparrow = B_k^j$;
- for $l \geq k + iJ$ and $i \geq 1$, if there is Q_k^j such that $Q_k^j \cap Q_l^{j'} \neq \emptyset$ and Q_k^j and $Q_l^{j'}$ belong to the same family then we say that $B_l^{j'}$ is a *descendant* of B_k^j and B_k^j is an *ancestor* of $B_l^{j'}$.

We extend the parent, child, and descendant relationships to net points x_k^j and $x_l^{j'}$ in the obvious way. By property (iii), when a ball or net point has a parent, the parent is unique. We say a collection $\mathcal{T} \subset \mathcal{C}^\mu$ is a *tree* if

1. there exists a unique $B_0 \in \mathcal{T}$ such that for every ball $B \in \mathcal{T}$, B is a descendant B_0 . We denote the ball B_0 by $\text{Top}(\mathcal{T})$ and we call B_0 the top of tree \mathcal{T} ;

2. for every $B \in \mathcal{T} \setminus \{B_0\}$, $B^\uparrow \in \mathcal{T}$.

A *branch* of \mathcal{T} is a sequence of balls

$$B_0 \succ B_1 \succ B_2 \succ \dots \text{ such that each } B_i \in \mathcal{T}.$$

A branch is finite if there is some $B_t \in \mathcal{T}$ such that for all $B_i \in \mathcal{T} \setminus \{B_t\}$, $B_t \not\succ B_i$. That is, no child of B_t is contained in the tree. If a branch is not finite then it is infinite. We define the *leaves* of the tree \mathcal{T} to be the set

$$\text{Leaves}(\mathcal{T}) := \bigcup \left\{ \lim_{i \rightarrow \infty} \overline{B}_i : B_0 \succ B_1 \succ B_2 \succ \dots \text{ is an infinite branch of } \mathcal{T} \right\}.$$

Here the limit is taken to be the intersection of nested sets, $\lim_{i \rightarrow \infty} \cap_{j=0}^{\infty} B_j$. Now we specify $\lambda_2 > (1 - 2^{-J})^{-2}$. This specification allows us to prove the following containment of children inside of parent balls.

Lemma 3.2.2. *If $B_l^{j'} \prec B_k^j$, then $B_l^{j'} \subset B_k^j$.*

Proof. Since $B_l^{j'} \prec B_k^j$, $(4\lambda_2)^{-1} B_l^{j'} \cap Q_{k,1}^j \neq \emptyset$. This implies that

$$\left| x_{B_l^{j'}} - x_{B_k^j} \right| \leq \sum_{i=1}^l 2^{-k-iJ} \leq 2^{-k} \left(\frac{1}{1 - 2^{-J}} \right).$$

Fix $y \in B_l^{j'}$, and observe that

$$\left| y - x_{B_k^j} \right| \leq \left| y - x_{B_l^{j'}} \right| + \left| x_{B_l^{j'}}, x_{B_k^j} \right| \leq (\lambda_2 2^{-J} + (1 - 2^{-J})^{-1}) 2^{-k}.$$

By the choice of λ_2 we have we have $\lambda_2(1 - 2^{-J}) > \frac{1}{1 - 2^{-J}}$, so $(\lambda_2 2^{-J} + (1 - 2^{-J})^{-1}) < \lambda_2 2^{-k}$.

It follows that $y \in B_k^j$. □

Now that a tree structure has been defined on \mathcal{C}^μ , we will show that a rectifiable curve can be drawn through the leaves of a tree. We begin with a lemma that relates the center of mass of a set to its L^2 beta number. This is an adaptation of [23, Lemma 6.4].

Lemma 3.2.3. *Let μ be a locally finite Borel measure on H , let E be a Borel set of positive diameter such that $0 < \mu(E) < \infty$, and let*

$$z_E := \int_E z \frac{d\mu(x)}{\mu(E)} \in H$$

denote the center of mass of E with respect to μ . For every straight line ℓ in H ,

$$\text{dist}(z_E, \ell) \leq \beta_2(\mu, E, \ell) \text{diam } E.$$

Proof. For every affine subspace ℓ in H , the function $\text{dist}(\cdot, \ell)^2$ is convex. Thus,

$$\text{dist}(z_E, \ell)^2 = \text{dist}\left(\int_E z \frac{d\mu(z)}{\mu(E)}, \ell\right)^2 \leq \int_E \text{dist}(z, \ell)^2 \frac{d\mu(z)}{\mu(E)} = \beta_2(\mu, E, \ell)^2 (\text{diam } E)^2$$

by Jensen's inequality. □

We will also need the following lemma which says that a compact connected set of finite length is a Lipschitz image.

Lemma 3.2.4 ([30], Lemma 3.7). *If $\Gamma \subset H$ is a closed, connected set such that $\mathcal{H}^1(\Gamma) < \infty$, then there exists a Lipschitz map $f : [0, 1] \rightarrow H$ such that $\Gamma = f([0, 1])$. Moreover, f can be found such that $|f(s) - f(t)| \leq 32\mathcal{H}^1(\Gamma)|s - t|$ for all $0 \leq s, t \leq 1$.*

Lemma 3.2.5 (Drawing rectifiable curves through the leaves of uniformly doubling trees, cf. [8, Lemma 3.7]). *Let μ be a finite measure on H and let $1 \leq D_{\mathcal{T}} < \infty$. If \mathcal{T} is a tree of balls from the*

multiresolution family \mathcal{C}^μ such that

$$\mu(B^\dagger) \leq D_{\mathcal{T}} \mu(B) \text{ for all } B \in \mathcal{T} \quad (3.2.1)$$

and

$$S_2(\mu, \mathcal{T}) := \sum_{B \in \mathcal{T}} \beta_2(\mu, 2B)^2 \operatorname{diam} B < \infty.$$

Additionally, suppose that \mathcal{T} satisfies the finite overlap property. Then there exists a rectifiable curve Γ in H such that $\Gamma \supset \operatorname{Leaves}(\mathcal{T})$ and

$$\mathcal{H}^1(\Gamma) \lesssim \operatorname{diam} \operatorname{Top}(\mathcal{T}) + D_{\mathcal{T}}^{6+J} S_2(\mu, \mathcal{T}).$$

Proof. By dilating and translating as needed, we may assume that $\operatorname{Top}(\mathcal{T}) = B(0, \lambda) =: B_0$. Deleting irrelevant balls from \mathcal{T} , we may also assume that every ball $B \in \mathcal{T}$ belongs to an infinite branch of \mathcal{T} . Our goal is apply Theorem C. Set parameters $C^* = 5 \cdot 2^J$, $r_0 = \operatorname{diam}(\operatorname{Top}(\mathcal{T})) = 2\lambda_2$, and $\delta = 2^{-J}$ where J is as in Lemma 3.2.1. For each $B \in \mathcal{T}$, let $z_B = \int_B z \frac{d\mu(z)}{\mu(B)}$ denote the center of mass of B , and for $k \geq 0$, set

$$Z_k = \{z_B : B \in \mathcal{T} \cap \mathcal{C}_k^\mu\}.$$

Choose V_k to be any maximal $\delta^k r_0$ -separated subset of Z_k , and fix $x_0 \in B_0$. Then

$$V_k \subset Z_k \subset \operatorname{Top}(\mathcal{T}) \subset B(x_0, r_0) \subset B(x_0, C^* r_0)$$

Clearly, V_k satisfies (V1) of Theorem C. It remains to verify that (V2) and (V3) hold. We begin with (V2). Let $k \geq 0$ and let $v \in V_k$, say $v = z_B$ for some $B \in \mathcal{T} \cap \mathcal{C}_k^\mu$. As a consequence of our

assumption that every ball in \mathcal{T} belongs to an infinite branch of \mathcal{T} , there exists $R \in \mathcal{T}$ such that R is a child of B . By maximality of V_{k+1} , there is $v' = z_P \in V_{k+1}$ for some $P \in \mathcal{T} \cap \mathcal{C}_{k+1}^\mu$ such that $|z_R - z_P| < \delta^{k+1}r_0$. It follows that

$$\begin{aligned}
|z_B - z_P| &\leq |z_B - z_R| + |z_R - z_P| \\
&\leq |z_B - x_B| + |x_B - x_R| + |x_R - z_R| + |z_R - z_P| \\
&\leq \frac{1}{2} \text{diam}(B) + \frac{1}{2} \text{diam}(Q_B) + \frac{1}{2} \text{diam}(Q_R) + \frac{1}{2} \text{diam}(R) + \delta^{k+1} \\
&\leq 4 \cdot \delta^k r_0 \\
&< C^* \delta^k r_0.
\end{aligned}$$

Thus condition (V2) is satisfied.

Finally, to check condition (V3), let $k \geq 1$ and let $v \in V_k$, say $v = z_B$ for some $B \in \mathcal{T} \cap \mathcal{C}_k^\mu$. Let R denote the parent of B which necessarily belongs to \mathcal{T} . By maximality, there exists $v' = z_P \in V_{k-1}$ for some P in the same generation as R with $|z_P - z_R| < \delta^{k-1}r_0$. It follows that

$$\begin{aligned}
|z_B - z_P| &\leq |z_B - z_R| + |z_R - z_P| \\
&\leq |z_B - x_B| + |x_B - x_R| + |x_R - z_R| + |z_R - z_P| \\
&\leq \frac{1}{2} \text{diam}(B) + \frac{1}{2} \text{diam}(Q_B) + \frac{1}{2} \text{diam}(Q_R) + \frac{1}{2} \text{diam}(R) + \delta^{k-1} \\
&\leq 5 \cdot 2^J r_0 \delta^k \\
&= C^* r_0 \delta^k,
\end{aligned}$$

so (V3) is satisfied as well.

Fix $k \geq 0$ and $v \in V_k$, and choose a ball $B_{k,v} \in \mathcal{T}$ such that $v = z_{B_{k,v}}$. That is, $B_{k,v}$ is the ball in \mathcal{C}_k^μ whose center of mass is v . For each $k \geq 1$ and $v \in V_k$, let $\hat{B}_{k,v} \in \mathcal{T}$ denote the minimal

ancestor of $B_{k,v}$ satisfying

- $\hat{B}_{k,v} \supset B_{k,v}$;
- for every $v' \in V_k \cap B(v, 66C^*\delta^{k-2}r_0)$ and $j \in \{k-1, k\}$, $\hat{B}_{k,v} \supset B_{j,v'}$

Now $66C^*\delta^{k-2}r_0 = 66 \cdot 2^{2J}C^*\delta^k r_0 < 2^{7+2J}\lambda_2\delta^k$, so

$$\frac{\text{diam } \hat{B}_{k,v}}{\text{diam } B_{k,v}} \leq 2^{12+2J}$$

for all $j \in \{k-1, k\}$ and $v' \in V_j \cap B(v, 66C^*\delta^{k-2}r_0)$. Furthermore, from assumption (3.2.1) we get that,

$$\frac{\mu(2\hat{B}_{k,v})}{\mu(2B_{j,v'})} \leq D_{\mathcal{T}}^{12+2J} \quad (3.2.2)$$

for all $j \in \{k-1, k\}$ and $v' \in V_j \cap B(v, 66C^*\delta^{k-2}r_0)$. Next, let $k \geq 1$ and let $v \in V_k$. Choose $\ell_{k,v}$ to be any straight line in H such that

$$\beta_2(\mu, 2\hat{B}_{k,v}, \ell_{k,v}) \leq 2\beta_2(\mu, 2\hat{B}_{k,v}). \quad (3.2.3)$$

Such line exists by definition of β -number. By combining estimate (3.2.2) and (3.2.3) we see that

$$\begin{aligned} \beta_2(\mu, 2B_{j,v'}, \ell_{j,v'}) \text{diam } B_{j,v'} &= \left(\int_{2B_{j,v'}} \left(\frac{\text{dist}(x, \ell_{k,v})}{\text{diam}(2B_{j,v'})} \right)^2 \frac{d\mu(x)}{\mu(2B_{j,v'})} \right)^{\frac{1}{2}} \text{diam}(B_{j,v'}) \\ &\leq \int_{2\hat{B}_{k,v}} \left(\left(\frac{\text{dist}(x, \ell_{k,v})}{\text{diam } \hat{B}_{k,v}} \right)^2 \frac{d\mu(x)}{\mu(2B_{j,v'})} \right)^{\frac{1}{2}} \text{diam } B_{k,v} \left(\frac{\text{diam } B_{j,v'}}{\text{diam } B_{k,v}} \right) \left(\frac{\text{diam } \hat{B}_{k,v}}{\text{diam } B_{j,v'}} \right) \left(\frac{\mu(2\hat{B}_{k,v})}{\mu(2B_{j,v'})} \right)^{\frac{1}{2}} \\ &\leq 2^{12+2J} D_{\mathcal{T}}^{6+J} \beta_2(\mu, 2\hat{B}_{k,v}, \ell_{k,v}) \text{diam } B_{k,v} \\ &\leq (4D_{\mathcal{T}})^{6+J} \beta_2(\mu, 2\hat{B}_{k,v}) \text{diam } B_{k,v} \\ &=: \alpha_{k,v} \delta^k r_0 \end{aligned}$$

for all $j \in \{k, k-1\}$ and all $v' \in B(v, 66C^*\delta^{k-2}r_0)$. This verifies the remaining hypothesis of Theorem C. Now since \mathcal{T} satisfies the finite overlap property, the number of times a ball $B \in \mathcal{T}$ appears as $\hat{B}_{k,v}$ is bounded, and the bound depends on at most the finite overlap constant $P(\mathcal{T}, 12+2J)$. We conclude that there exists a compact, connected set $\Gamma \subset H$ such that

$$\mathcal{H}^1(\Gamma) \lesssim_{C^*} r_0 + \sum_{k=1}^{\infty} \sum_{v \in V_k} \alpha_{k,v}^2 \delta^k r_0 \lesssim \text{diam Top}(\mathcal{T}) + d_{\mathcal{T}}^{6+J} S_p(\mu, \mathcal{T}),$$

and $\Gamma \supset V = \lim_{k \rightarrow \infty} V_k$. By Lemma 3.2.4, Γ is a rectifiable curve. It remains to check that $\Gamma \supset \text{Leaves}(\mathcal{T})$.

Let $y \in \text{Leaves}(\mathcal{T})$, say $y = \lim_{k \rightarrow \infty} y_k$ for a sequence of points $y_k \in \overline{B}_k$ corresponding to an some infinite branch $B_0 \succ B_1 \succ B_2 \succ \dots$ of \mathcal{T} . Let $z_k = z_{B_k}$ denote the center of mass of B_k and let $v_k \in V_k$ be any point which minimizes distance to z_k . By maximality of the net V_k , $|z_k - v_k| \leq \delta^k r_0$. Furthermore, since both z_k and y_k live in B_k , $|z_k - y_k| \leq \text{diam } B_k = \delta^k r_0$. Combining these estimates, we get

$$|v_k - y| \leq |v_k - z_k| + |z_k - y_k| + |y_k - y| \leq 2 \cdot \delta^k r_0 + |y_k - y| \text{ for all } k \geq 0.$$

Thus $y = \lim_{k \rightarrow \infty} v_k \in \lim_{k \rightarrow \infty} V_k \subset \Gamma$. Since $y \in \text{Leaves}(\mathcal{T})$ arbitrary, we conclude that $\Gamma \supset \text{Leaves}(\mathcal{T})$. \square

We now prove a lemma which is an adaptation of [8, Lemma 5.6] to the setting of trees on which μ satisfies a doubling property. Let \mathcal{T} be a tree of balls in \mathcal{C}^μ , and define a μ -normalized sum function by

$$\hat{S}_{\mathcal{T},b}(\mu, x) := \sum_{B \in \mathcal{T}} \frac{b(B)}{\mu(B)} \chi_B(x) \text{ for all } x \in H.$$

We interpret $0/0 = 0$ and $1/0 = \infty$. The following result hold.

Lemma 3.2.6 (Localization lemma for doubling tree). *Let $\mathcal{T} \subset \mathcal{C}^\mu$ be a tree, and suppose that there exists a constant $D_{\mathcal{T}}$ such that $\mu(B) \leq D_{\mathcal{T}}\mu(aB)$ for every $B \in \mathcal{T}$ where a is some fixed constant satisfying some $0 < a \leq c$. Here c is as in Lemma 3.2.1. Let $b : \mathcal{T} \rightarrow [0, \infty)$. Then for all $N < \infty$, and $\epsilon > 0$, there exists a partition of \mathcal{T} into a set $\text{Good}(\mathcal{T}, N, \epsilon)$ of good balls and a set $\text{Bad}(\mathcal{T}, N, \epsilon)$ of bad balls with the following properties.*

(i) *Either $\text{Good}(\mathcal{T}, N, \epsilon) = \emptyset$ or $\text{Good}(\mathcal{T}, N, \epsilon)$ is tree of balls from \mathcal{C}^μ with*

$$\text{Top}(\text{Good}(\mathcal{T}, N, \epsilon)) = \text{Top}(\mathcal{T}).$$

(ii) *Every child of a bad ball is a bad ball: if B and R belong to \mathcal{T} , $R \in \text{Bad}(\mathcal{T}, N, \epsilon)$ and $B \prec R$, then $B \in \text{Bad}(\mathcal{T}, N, \epsilon)$.*

(iii) *The set $E := \{x \in \text{Top}(\mathcal{T}) : S_{\mathcal{T}, b}(\mu, x) \leq N\}$ and $E' := E \cap \text{Leaves}(\text{Good}(\mathcal{T}, N, \epsilon))$ have comparable measures:*

$$\mu(E') \geq (1 - \epsilon\mu(\text{Top}(\mathcal{T})))\mu(E).$$

(iv) *The sum of the function b over the good cubes is finite*

$$\sum_{B \in \text{Good}(\mathcal{T}, N, \epsilon)} b(B) < \frac{ND_{\mathcal{T}}}{\epsilon}.$$

Proof. Suppose that \mathcal{T} , μ , b , N , ϵ , E , and E' are as given in the statement of the lemma. If $\mu(E) = 0$ then we may declare every ball $B \in \mathcal{T}$ to be a bad ball, and the conclusion of the lemma holds trivially. Therefore, suppose that $\mu(E) > 0$. Declare a ball $B \in \mathcal{T}$ to be a bad ball if there exists a ball $B' \in \mathcal{T}$ such that B is a descendant of B' and B' satisfies

$$\mu(E \cap B') \leq \epsilon\mu(E)\mu(Q_{B'})$$

where $Q_{B'}$ is the core of the ball B' . We call B a good ball if B is not a bad ball. Properties (i) and (ii) are immediately satisfied by the definitions of good and bad balls. To check property (iii) we remark that $E \setminus \text{Leaves}(\text{Good}(\mathcal{T}, N, \epsilon)) \subset E \cap \bigcup_{B \in \text{Bad}(\mathcal{T}, N, \epsilon)} B$. Let $\text{Bad}_M(\mathcal{T}, N, \epsilon) \subset \text{Bad}(\mathcal{T}, N, \epsilon)$ denote the set of maximal bad balls. That is, $B \in \text{Bad}_M(\mathcal{T}, N, \epsilon)$ if no ancestor of B is a bad ball. Then

$$\begin{aligned}
\mu(E \setminus E') &\leq \mu \left(E \cap \bigcup_{B \in \text{Bad}(\mathcal{T}, N, \epsilon)} B \right) \\
&\leq \mu \left(E \cap \bigcup_{B \in \text{Bad}_M(\mathcal{T}, N, \epsilon)} B \right) \\
&\leq \sum_{B \in \text{Bad}_M(\mathcal{T}, N, \epsilon)} \mu(E \cap B) \\
&\leq \epsilon \mu(E) \sum_{B \in \text{Bad}_M(\mathcal{T}, N, \epsilon)} \mu(Q_B) \\
&\leq \epsilon \mu(E) \mu \left(\bigcup_{B \in \text{Bad}(\mathcal{T}, N, \epsilon)} Q_B \right) \\
&\leq \epsilon \mu(E) \mu(\text{Top}(\mathcal{T})).
\end{aligned}$$

Note that for the second inequality we use Lemma 3.2.2 and for the penultimate inequality we use that the cores of the maximal balls are disjoint by Property (iv) of Lemma 3.2.1. Thus

$$\mu(E') = \mu(E) - \mu(E \setminus E') \geq (1 - \epsilon \mu(\text{Top}(\mathcal{T}))) \mu(E)$$

so property (iii) holds.

Before we begin the proof of (iv), we recall that by definition of \mathcal{T} and by the construction of

cores Q_B ,

$$\mu(B) \leq D_{\mathcal{T}}\mu(aB) \leq D_{\mathcal{T}}\mu(Q_B). \quad (3.2.4)$$

Finally, since $\hat{S}_{\mathcal{T},b}(\mu, x) \leq N$ for all $x \in E$,

$$\begin{aligned} N\mu(E) &\geq \int_E \hat{S}_{\mathcal{T},b}(\mu, x) d\mu(x) \\ &\geq \int_E \sum_{B \in \mathcal{T}} \frac{b(B)}{\mu(B)} \chi_B(x) d\mu(x) \\ &\geq \frac{1}{D_{\mathcal{T}}} \sum_{B \in \mathcal{T}} b(B) \frac{\mu(E \cap B)}{\mu(Q_B)} \\ &\geq \frac{\epsilon}{D_{\mathcal{T}}} \mu(E) \sum_{B \in \text{Good}(\mathcal{T}, N, \epsilon)} b(B). \end{aligned}$$

The second to last inequality follows by (3.2.4), and the last equality holds because balls in $\text{Good}(\mathcal{T}, N, \epsilon)$ satisfy $\mu(E \cap B) > \epsilon\mu(E)\mu(Q_B)$. We conclude that $\sum_{B \in \text{Good}(\mathcal{T}, N, \epsilon)} b(B) \leq ND_{\mathcal{T}}/\epsilon$. \square

Theorem 3.2.1. *Let μ be a pointwise doubling measure on H . Then the measure*

$$\mu \llcorner \left\{ x \in H : \hat{J}_2(\mu, x) < \infty \right\}$$

is 1-rectifiable.

Proof. Fix $x \in H$ be a μ -typical point. Then there exists $1 \leq \omega_x < \infty$ and $r_x > 0$ such that $\mu(B(x, 2r)) \leq 2^{\omega_x} \mu(B(x, r))$ for all $0 < r < r_x$. Let a' be an integer such that $2^{a'} \geq 1/c$, where c is as in Lemma 3.2.1. Then

$$\mu(B) \leq \mu(B(x, \text{diam}(B))) \leq 2^{(a'+1)\omega_x} \mu\left(B\left(x, \text{radius}\left(2^{-(a'+1)}B\right)\right)\right) \leq D_{\lambda_2, \omega_x} \mu(cB)$$

for every $B \in \mathcal{C}^\mu$ such that $x \in 2^{-(a'+1)}B$ and $\text{radius}(B) < r_x$. A similar series of inequalities shows that if $B' \prec B$ then $B \subset 2^{J+2}B'$ and

$$\mu(B) \leq \mu(2^{J+2}B') \leq d_{\omega_x} \mu(B')$$

for some constant d_{ω_x} depending on ω_x . Thus, x belongs to the leaves of the tree

$$\mathcal{T}_x = \{B \in \mathcal{C}^\mu : B \prec B_x, \mu(R) \leq D_{\lambda_2, \omega_x} \mu(cR), \mu(R^\dagger) \leq d_{\omega_x} \mu(R) \text{ for all } R \in \mathcal{C}^\mu \text{ s.t. } B \prec R \prec B_x\},$$

where $B_x \ni x$ is defined to be a maximal ball in a family satisfying $\text{radius}(8B) < r_x$. By Lemma 3.2.2, $x \in \text{Top}(\mathcal{T}_x) \cap \text{Leaves}(\mathcal{T}_x)$. Now since each tree \mathcal{T}_x is determined by $B_x \in \mathcal{C}^\mu$ and \mathcal{C}^μ is countable, we can enumerate the trees

$$\left\{ \mathcal{T}_x : \limsup_{x \downarrow 0} \mu(B(x, 2r)) / \mu(B(x, r)) < \infty \right\} = \{\mathcal{T}_{x_i}, i = 1, 2, 3, \dots\}$$

for $x_i \in \text{spt } \mu$. Thus,

$$\begin{aligned} & \left\{ x \in H : \limsup_{x \downarrow 0} \mu(B(x, 2r)) / \mu(B(x, r)) < \infty \text{ and } \hat{J}_2(\mu, x) < \infty \right\} \\ & \subset \bigcup_{i=1}^{\infty} \bigcup_{j=1}^{\infty} \{x \in \text{Top}(\mathcal{T}_{x_i}) : \hat{J}_2(\mu, x) \leq j\}, \end{aligned}$$

so it suffices to prove that the measure $\mu \llcorner A_{y,N}$ is 1-rectifiable for arbitrary y in the carrying set X such that $\hat{J}_2(\mu, y) \leq N$ where

$$A_{y,N} := \{x \in \text{Top}(\mathcal{T}_y) : \hat{J}_2(\mu, x) \leq N\}.$$

Fix such y and N . Set $\eta_y := \mu(\text{Top}(\mathcal{T}_y))$. Given $0 < \epsilon < \eta_y$, let $\mathcal{T}_{y,N,\epsilon} := \text{Good}(\mathcal{T}_y, N, \epsilon) \subset \mathcal{T}_y$

denote the tree given by Lemma 3.2.6 with $\mathcal{T} = \mathcal{T}_y$, $b(Q) = \beta_2(\mu, 2B)^2 \text{diam } B$, and $a = c$. Then by Lemma 3.2.6, $S_2(\mu, \mathcal{T}_{y,N,\epsilon}) < ND_{\mathcal{T}_{y,N,\epsilon}}/\epsilon$ and

$$\mu(A_{y,N} \cap \text{Leaves}(\mathcal{T}_{y,N,\epsilon})) \geq (1 - \epsilon\eta_y)\mu(A_{y,N}).$$

By Lemma 3.2.5, there exists a rectifiable curve $\Gamma_{y,N,\epsilon}$ in H such that $\Gamma_{y,N,\epsilon}$ captures a significant portion of the mass of $A_{y,N}$:

$$\mu(A_{y,N} \setminus \Gamma_{y,N,\epsilon}) \leq \mu(A_{y,N}) - \mu(A_{y,N} \cap \Gamma_{y,N,\epsilon}) \leq \mu(A_{y,N}) - (1 - \epsilon\eta_y)\mu(A_{y,N}) = \epsilon\eta_y\mu(A_{y,N}).$$

Finally, for $k \geq 1$, choose $0 < \epsilon_k < \eta_y$ such that $\lim_{k \rightarrow \infty} \epsilon_k = 0$. Then

$$\mu\left(A_{y,N} \setminus \bigcup_{k=1}^{\infty} \Gamma_{y,N,\epsilon_k}\right) \leq \inf_{k \geq 1} \mu(A_{y,N} \setminus \Gamma_{y,N,\epsilon_k}) \leq \eta_y\mu(A_{y,N}) \inf_{k \geq 1} \epsilon_k = 0.$$

We conclude that $\mu \llcorner A_{y,N}$ is 1-rectifiable. This completes the proof. \square

An immediate corollary of this result is the sufficient direction of Theorem A.

3.3 The decomposition of μ

We are now ready to prove the decomposition result, Theorem B.

Proof of Theorem B. Let μ be a pointwise doubling measure on an infinite dimensional Hilbert space H , and partition H into two sets:

$$R = \{x \in H : \hat{J}(\mu, x) < \infty\} \text{ and } P = \{x \in H : \hat{J}(\mu, x) = \infty\}.$$

It is clear that both R and P are Borel sets. Since R and P partition H , we have

$$\mu = \mu \llcorner R + \mu \llcorner P \text{ and } \mu \llcorner R \perp \mu \llcorner P.$$

The decomposition $\mu = \mu_{\text{rect}} + \mu_{\text{pu}}$ is unique (see [8, Theorem 1.2]), so to prove Theorem B it suffices to show that $\mu \llcorner R$ is rectifiable and $\mu \llcorner P$ is purely unrectifiable. By Theorem 3.2.1, $\mu \llcorner R$ is 1-rectifiable. Additionally,

$$\mu \llcorner P \leq \mu \llcorner \{x \in H : \underline{D}^1(\mu, x) = 0\} + \mu \llcorner \{x \in H : \underline{D}^1(\mu, x) > 0 \text{ and } \hat{J}_2(\mu, x) = \infty\}.$$

By Theorem 3.1.2 $\mu \llcorner \{x \in H : \underline{D}(\mu, x) = 0\}$ is purely unrectifiable, and by Theorem 3.1.3 $\mu \llcorner \{x \in H : \underline{D}^1(\mu, x) > 0 \text{ and } \hat{J}_2(\mu, x) = \infty\}$ is purely unrectifiable. Therefore, $\mu \llcorner P$ is also purely unrectifiable. This completes the proof of Theorem B.

□

3.4 An example of a rectifiable pointwise doubling measure with infinite dimensional support

In this section we construct a pointwise doubling measure μ which has infinite dimensional support, is carried by Lipschitz images, and assigns zero measure to every bi-Lipschitz image. To construct the measure, we build off a construction by Garnett, Killip, and Schul of a doubling measure on \mathbb{R}^n which is carried by Lipschitz images but singular to bi-Lipschitz images.

Theorem 3.4.1 (Garnett, Killip Schul [18]). *For $n \geq 2$ there exists a 1-rectifiable doubling measure ν^n with $\text{spt } \nu^n = \mathbb{R}^n$.*

Let $\nu = \nu^2$ be as in [18], and let C_ν denote the doubling constant. Let $V_0 \in H$ be a two

dimensional linear plane. Fix a basis on H so that for $x \in V_0$, $x = (a_1, a_2, 0, 0, \dots)$ for some $a_1, a_2 \in \mathbb{R}$. By the separability of H choose a dense collection $\{x_i\}_{i=1}^\infty$ of V_0^\perp , the orthogonal complement of V_0 . Set $V_i = V_0 + x_i$. We identify each V_i , $i = 0, 1, 2, 3, \dots$ with \mathbb{R}^2 using the map $\pi_i : V_i \rightarrow \mathbb{R}^2$ defined by

$$\pi_i((a_1, a_2, a_3, \dots)) = (a_1, a_2).$$

Let $\{c_i\}_{i=0}^\infty$ be a summable sequence of positive numbers, i.e., $c_i > 0$ for each i and $\sum_{i=1}^\infty c_i < \infty$. Then set $\mu := \sum_{i=0}^\infty c_i \nu_i$ where $\nu_i(E) := \nu(\pi_i(E \cap V_i))$. In particular, for $y \in V_i$

$$\nu_j(B(y, r)) := \nu(B(\pi_j(y), S_r^{ij})),$$

where

$$S_r^{ij} := \begin{cases} \sqrt{r^2 - \text{dist}^2(V_i, V_j)}, & \text{if } \text{dist}(V_i, V_j) < r \\ 0 & \text{otherwise.} \end{cases}$$

Since ν is rectifiable, μ is also rectifiable. That μ is finite on bounded sets follows from the summability of the sequence $\{c_i\}$ together with the fact that ν is finite on bounded sets. Furthermore, μ -a.e. y is an element of some point V_i . Now fix some such y and denote by V_{i_y} the plane that contains this y . Choose $N_y > i_y$ such that $\sum_{N_y+1}^\infty c_i \leq \frac{c_{i_y}}{2}$. For $2r < \min_{\{1, \dots, N_y\} \setminus \{i_y\}} \text{dist}(V_{i_y}, V_i) > 0$,

$$\begin{aligned} \mu(B(y, 2r)) &= \sum_{i=1}^{N_y} c_i \nu_i(B(y, 2r)) + \sum_{i=N_y+1}^\infty c_i \nu_i(B(y, 2r)) \\ &= c_{i_y} \nu_{i_y}(B(y, 2r)) + \sum_{i=N_y+1}^\infty c_i \nu(B(\pi_i(y), S_2^{i_y i} r)) \\ &\leq c_{i_y} \nu_{i_y}(B(y, 2r)) + \nu_{i_y}(B(y, 2r)) \sum_{i=N_y+1}^\infty c_i \\ &\leq c_{i_y} \nu_{i_y}(B(y, 2r)) + \frac{c_{i_y}}{2} \nu_{i_y}(B(y, 2r)) \end{aligned}$$

$$\leq c_{i_y} \nu_{i_y}(B(y, 2r)) + \frac{\mu(B(y, 2r))}{2}.$$

It follows that

$$\mu(B(y, 2r)) \leq 2c_{i_y} \nu_{i_y}(B(y, 2r)) = 2c_{i_y} \nu(B(\pi(y), 2r)) \leq 2c_{i_y} C_\nu \nu(B(\pi(y), r)) \leq 2C_\nu \mu(B(y, r)).$$

Thus for every μ -a.e. y ,

$$\limsup_{r \downarrow 0} \frac{\mu(B(y, 2r))}{\mu(B(y, r))} \leq 2C_\nu$$

so μ is a pointwise doubling measure. By the density of the collection $\{x_i\}_{i=1}^\infty$, and since the coefficients c_i were chosen to be nonzero, $\text{spt}(\mu) = H$.

Chapter 4

Drawing curves through nets: an Analyst's Traveling Salesman Algorithm

In this section we prove Theorem C. The proof follows the same outline as the proof of Proposition 3.6 in [8]. We provide full details to the portions of the proof that require adaptations to the setting of infinite dimensional Hilbert space, and we refer the reader to appropriate sections in [8] for portions that follow identically. The required adaptations, which serve to remove dimension dependence, draw on ideas from [30] and [6]. We begin by restating Theorem C for convenience.

Theorem C. Let H be a separable, infinite dimensional Hilbert space. Let $C^* > 1$, let $x_0 \in H$, $0 < \delta \leq 1/2$, and $r_0 > 0$. Let $\{V_k\}_{k=0}^\infty$ be a sequence of nonempty, finite subsets of $B(x_0, C^*r_0)$ such that

- (V1) distinct points $v, v' \in V_k$ are uniformly separated: $|v - v'| \geq \delta^k r_0$;
- (V2) for all $v_k \in V_k$, there exists $v_{k+1} \in V_{k+1}$ such that $|v_{k+1} - v_k| < C^* \delta^k r_0$;
- (V3) for all $v_k \in V_k$ there exists $v_{k-1} \in V_{k-1}$ such that $|v_{k-1} - v_k| < C^* \delta^k r_0$.

Suppose that for all $k \geq 1$ and for all $v \in V_k$, we are given a straight line $\ell_{k,v}$ in H and a number $\alpha_{k,v} \geq 0$ such that

$$\sup_{x \in (V_{k-1} \cup V_k) \cap B(v, 66C^*\delta^{k-2}r_0)} \text{dist}(x, \ell_{k,v}) \leq \alpha_{k,v}\delta^k r_0,$$

and

$$\sum_{k=1}^{\infty} \sum_{v \in V_k} \alpha_{k,v}^2 \delta^k r_0 < \infty.$$

Then the sets V_k converge in the Hausdorff metric to a compact set $V \subset B(x_0, C^*r_0)$, and there exists a compact connected set such that $\Gamma \subset \overline{B(x_0, C^*r_0)}$ such that $\Gamma \supset V$ and

$$\mathcal{H}^1(\Gamma) \lesssim_{C^*, \delta} r_0 + \sum_{k=1}^{\infty} \sum_{v \in V_k} \alpha_{k,v}^2 \delta^k r_0.$$

As in [8], we prove Theorem C in three parts. In section 4.1 we construct sets Γ_k by connecting vertices in V_k with straight line segments. In section 4.2 we verify that the sets Γ_k are connected. Finally, in section 4.3 we justify the length estimate on the limiting set. For ease of notation, we assume that $r_0 = 1$ throughout our construction of the curves. We will need the following two lemmas.

Lemma 4.0.1. *Let $B \subset H$ be a bounded set and let V_0, V_1, \dots be a sequence of nonempty finite subsets of B . If the sequence satisfies (V2) and (V3) for some $C^* > 0$ and $r_0 > 0$ then V_k converges in the Hausdorff metric to a closed set $V \subset \overline{B}$.*

The proof of this lemma relies on fundamental properties of excess and Hausdorff distance. For nonempty sets $S, T \subset X$, the excess, $ex(S, T)$ of S over T is defined by

$$ex(S, T) := \sup_{s \in S} \inf_{t \in T} \text{dist}(s, t),$$

and the Hausdorff distance $HD(S, T)$ between S and T is defined by

$$HD(S, T) := \max\{ex(S, T), ex(T, S)\}.$$

Let $CL(H)$ denote the set of nonempty closed subsets of H . Since $(H, |\cdot|)$ is a complete metric space, $(CL(H), HD)$ is also a complete metric space. See [9, Chapter 3], for details.

Proof. Let $n \geq 1$, $C^* > 1$, $\delta \leq 1/2$ and $r_0 > 0$. Assume that V_0, V_1, V_2, \dots is a sequence of nonempty, closed finite subsets of a bounded set B such that each V_i satisfies (V2) and (V3). By iterating (V2), we obtain that for any $k < j$ and $v_k \in V_k$, there exists a sequence of $v_i \in V_i$, $i = k+1, \dots, j$ such that

$$|v_k - v_j| \leq |v_k - v_{k+1}| + \dots + |v_{j-1} - v_j| < C^* \delta^k r_0 + \dots + C^* \delta^{j-1} r_0 \leq 2C^* \delta^k.$$

It follows that $ex(V_k, V_j) < 3C^* \delta^k r_0$. Similarly iterating (V3), we obtain that for any $k < j$, $ex(V_j, V_k) < 3C^* \delta^k r_0$. Thus $HD(V_k, V_j) \leq 2C^* \delta^k r_0$. In particular this implies that $\{V_k\}$ is a Cauchy sequence of sets. By the completeness of $(CL(H), HD)$, $\{V_k\}$ converges to a closed set V . \square

Lemma 4.0.2 ([8, Lemma 8.3]). *Suppose that $V \subset \mathbb{R}^n$ is a 1-separated set with $\#V \geq 2$ and there exist lines ℓ_1 and ℓ_2 and a number $0 \leq \alpha \leq 1/16$ such that*

$$\text{dist}(v, \ell_i) \leq \alpha \text{ for all } v \in V \text{ and } i = 1, 2.$$

Let π_i denote the orthogonal projection onto ℓ_i . There exist compatible identifications of ℓ_1 and ℓ_2 with \mathbb{R} such that $\pi_1(v') \leq \pi_1(v'')$ if and only if $\pi_2(v') \leq \pi_2(v'')$ for all $v', v'' \in V$. If v_1 and v_2 are

consecutive points in V relative to the ordering of $\pi_1(V)$, then

$$\mathcal{H}^1([u_1, u_2]) \leq (1 + 3\alpha^2) \cdot \mathcal{H}^1([\pi_1(u_1), \pi_1(u_2)]) \text{ for all } [u_1, u_2] \subset [v_1, v_2].$$

Moreover,

$$\mathcal{H}^1([y_1, y_2]) \leq (1 + 12\alpha^2) \cdot \mathcal{H}^1([\pi_1(y_1), \pi_1(y_2)]) \text{ for all } [y_1, y_2] \subset \ell_2.$$

Lemma 4.0.1 is an analogue to [8, Lemma 8.2] in the setting of Hilbert space. However, the proof presents a different proof technique to overcome the fact the closed, bounded sets are not necessarily compact in Hilbert space. Although H may be infinite dimensional, we will apply Lemma 4.0.2 to V_k for each k . Since V_k is a finite collection of points we may think of V_k as being embedded in \mathbb{R}^{n_k} where n_k is at least the cardinality of V_k .

4.1 Description of curves

We fix a parameter $0 < \epsilon < 1/32$ so that the conclusions of Lemma 4.0.2 hold for $\alpha = 2\epsilon$. This parameter will be used throughout our definition of Γ_k . For each k , we partition V_k into a set of vertices with $\alpha_{k,v}$ less than ϵ and a set of vertices with $\alpha_{k,v}$ greater than or equal to ϵ . That is, we set $V_k = V_k^{\text{Flat}} \cup V_k^{\text{Non-flat}}$ where $V_k^{\text{Flat}} = \{v \in V_k : \alpha_{k,v} < \epsilon\}$ and $V_k^{\text{Non-flat}} = \{v \in V_k : \alpha_{k,v} \geq \epsilon\}$. Our construction of Γ_k near a vertex v depends on whether $v \in V_k^{\text{Flat}}$ or $v \in V_k^{\text{Non-flat}}$.

We construct curves Γ_k to be the union of finitely many closed sets which take two forms.

1. *edges* $[v', v'']$: closed line segments between vertices $v', v'' \in V_k$.
2. *bridges* $B[j, w', w'']$: closed sets that connect vertices $w', w'' \in V_j$ for some $k_0 \leq j \leq k$ and pass through vertices of generation j' nearby w' and w'' for every $j' > j$. More explicitly,

for $j \geq k_0$ and $v \in V_j$ define an extension $e[j, v]$ in the following way. Given $v_0 = v$, pick a sequence of vertices v_1, v_2, \dots , inductively so that v_1 is a vertex in V_{j+1} that is closest to v_0 , v_2 is a vertex in V_{j+2} that is closest to v_1 , etc. Then define $e[j, v] := \overline{\bigcup_{i=0}^{\infty} [v_i, v_{i+1}]}$. Once extensions have been chosen, for each generation $j' \geq j$ we define the bridge $B[j, w', w'']$ by

$$B[j, w', w''] := e[j, w'] \cup [w', w''] \cup e[j, w''].$$

If an edge $[v', v'']$ is included in Γ_k , then $|v' - v''| < 30C^*\delta^{k-1}$. We will store edges constructed in generation k in a set denoted by $\text{Edge}(k)$. We will store each bridge in one of two sets: $\text{Bridge}_{\text{Flat}}(k)$ or $\text{Bridge}_{\text{Non-flat}}(k)$. We will add bridges to $\text{Bridge}_{\text{Flat}}(k)$ when we are constructing a portion of Γ_k nearby a vertex v satisfying $\alpha_{k,v} < \epsilon$, and we will add bridges to $\text{Bridge}_{\text{Non-flat}}(k)$ when we are constructing Γ_k for vertices v with $\alpha_{k,v} \geq \epsilon$. We denote the set of all bridges by $\text{Bridge}(k) := \text{Bridge}_{\text{Flat}}(k) \cup \text{Bridge}_{\text{Non-flat}}(k)$. Bridges are frozen in that if a bridge $B[k, v', v'']$ appears in Γ_k for some k then that $B[k, v', v'']$ also appears in $\Gamma_{k'}$ for all $k' \geq k$. We will need the following definition of semi-flat vertices to build Γ_k near non-flat vertices.

Definition 4.1.1 (Semi-flat vertex). For $k \geq k_0 + 1$, we call a vertex $y \in V_{k-1}$ a semi-flat vertex if $\alpha_{k-1,y} \geq \epsilon$ and there exists a vertex $v \in V_k$ such that $|y - v| \leq 32C^*\delta^{k-1}$ and $\alpha_{k,v} \leq \epsilon$.

Given a semi-flat vertex $y \in V_{k-1}$, we can choose vertex $v \in V_k^{\text{Flat}}$ such that $|v - y| \leq 32C^*\delta^{k-1}$. Then since $B(y, 33C^*\delta^{k-2}) \subset B(v, 66C^*\delta^{k-2})$, there exists a natural linear ordering on the points in $V_{k-1} \cap B(y, 33C^*\delta^{k-2})$ defined in terms of projection onto $\ell_{k,v}$. We define a set S_k of edges emanating from semi-flat vertices in V_k in the following way. Fix a semi-flat vertex y , and enumerate the points in $V_{k-1} \cap B(y, 33C^*\delta^{k-2})$ from left to right:

$$y_{-l}, \dots, y_{-1}, y_0 = y, y_1, \dots, y_m.$$

Add edges $[y_i, y_{i+1}]$ to S_k for $0 \leq i \leq m-1$ until $|y_i - y_{i+1}| \geq 30C^*\delta^{k-2}$ or until y_{i+1} does not exist. We symmetrically add edges to S_k between vertices to the left of y .

If $\#V_k = 1$ for infinitely many k then we can choose Γ_k to be a singleton and the theorem holds trivially. Thus let $k_0 \geq 1$ be the smallest index such that $\#V_k \geq 2$ for all $k \geq k_0$. It suffices then to describe the construction of Γ_k for $k \geq k_0$. We will first describe the construction of Γ_{k_0} . The subsequent constructions follow by induction on k .

Base Case: The construction of Γ_{k_0}

We claim that for any $v \in V_{k_0}$, $V_{k_0} \subset B(v, 2C^*\delta^{k_0}) \subset B(v, 66C^*\delta^{k_0-2})$. To see that this is true, recall that by definition of k_0 , there is a unique element $w \in V_{k_0-1}$. Additionally, by (V3), for any $v, v' \in V_{k_0}$, we have $|v - w| \leq C^*\delta^{k_0}$ and $|v' - w| \leq C^*\delta^{k_0}$. Hence,

$$|v - v'| \leq |v - w| + |w - v'| \leq 2C^*\delta^{k_0}.$$

Now suppose that $V_{k_0}^{\text{Flat}} \neq \emptyset$, and fix some element v_0 in the set. By Lemma 4.0.2 there exists a linear ordering on V_{k_0} ,

$$v_{-l}, \dots, v_{-1}, v_0, v_1, \dots, v_m$$

according to orthogonal projection onto the line ℓ_{k_0, v_0} . We connect v_i to v_{i+1} with an edge $[v_i, v_{i+1}]$ for all $-l \leq i \leq m$. We store each edge in $\text{Edge}(k_0)$.

Suppose instead that $V_{k_0}^{\text{Flat}} = \emptyset$. If there exists $v_0 \in V_{k_0}^{\text{Non-flat}}$ which is semi-flat with respect to some $y \in V_{k_0+1}$ then the vertices in V_{k_0} can be ordered according to projection on $\ell_{k_0+1, y}$, and we add edges as in the case when $V_{k_0}^{\text{Flat}} \neq \emptyset$. Otherwise, enumerate the vertices in V_{k_0} arbitrarily as v_0, v_1, \dots, v_m and connect v_i to v_{i+1} with the edge $[v_i, v_{i+1}]$ for $0 \leq i \leq m-1$. We store each edge in $\text{Edge}(k_0)$. In any case, we define Γ_{k_0} to be the union of edges in $\text{Edge}(k_0)$.

Inductive Case: The construction of Γ_k from Γ_{k-1}

Suppose $\Gamma_{k_0}, \dots, \Gamma_{k-1}$ have been defined for some $k \geq k_0 + 1$. To define the next set Γ_k we describe the construction of $\Gamma_{k,v}$, the new part of Γ_k nearby v for every $v \in V_k$. We will first describe the construction of $\Gamma_{k,v}$ for $v \in V_k^{\text{Flat}}$, and we will subsequently describe the construction of $\Gamma_{k,v}$ for $v \in V_k^{\text{Non-flat}}$. We refer to construction near vertices in V_k^{Flat} as “**Case F** construction” and construction near vertices in $V_k^{\text{Non-flat}}$ as “**Case N** construction.” As mentioned above, edges added in each stage of construction are include in $\text{Edge}(k)$, and bridges added during **Case F** are included in $\text{Bridge}_{\text{Flat}}(k)$ whereas bridges added during **Case N** are included in $\text{Bridge}_{\text{Non-flat}}(k)$.

Case F Construction

This step of construction follows identically to the case of vertices v satisfying $\alpha_{k,v} < \epsilon$ in Section 8.2 of [8] with $30C^*\delta^{k-1}$ in place of $30C^*2^{-k}$ and $66C^*\delta^{k-2}$ in place of $65C^*2^{-k}$. We include further exposition in order to introduce notation that will be used later in the paper.

Fix $v \in V_k^{\text{Flat}}$. Identify $\ell_{k,v}$ with \mathbb{R} (and pick a direction “left” and “right”). Let $\pi_{k,v}$ denote orthogonal projection onto $\ell_{k,v}$. Since $\alpha_{k,v} \leq \epsilon$, by Lemma 4.0.2 and (V1), both $V_k \cap B(v, 66C^*\delta^{k-2})$ and $V_{k-1} \cap B(v, 66C^*\delta^{k-2})$ can be arranged linearly along $\ell_{k,v}$. Set $v_0 = v \in V_k$ and let

$$v_{-l}, \dots, v_{-1}, v_0, v_1, \dots, v_m$$

denote the vertices in $V_k \cap B(v, 66C^*\delta^{k-2})$ arranged from left to right relative to the order of $\pi_{k,v}(v_i)$ in $\ell_{k,v}$. We will first describe the construction of the “right half”, $\Gamma_{k,v}^R$, of $\Gamma_{k,v}$. Starting with v_0 and working right, include each closed line segment $[v_i, v_{i+1}]$ as an edge in $\Gamma_{k,v}^R$ until one of the following holds:

- $|v_{i+1} - v_i| \geq 30C^*\delta^{k-1}$

- $v_{i+1} \notin B(v, 30C^*\delta^{k-1})$
- v_{i+1} is undefined.

Let $t \geq 0$ denote the number of edges that were included in $\Gamma_{k,v}^R$. We consider three subcases:

Case F-NT: If $t \geq 1$ then the vertex v is *non-terminal* to the right, and we are done describing $\Gamma_{k,v}^R$.

Case F-T: If $t = 0$ then v is a *terminal vertex*. We determine the construction of Γ_k by studying the behavior of Γ_{k-1} nearby v . Let w_v be a vertex in V_{k-1} that is closest to v . Enumerate the vertices in $V_{k-1} \cap B(v, 33C^*\delta^{k-2})$ starting from w_v and moving right

$$w_v = w_{v,0}, w_{v,1}, \dots, w_{v,s}.$$

Let $w_{v,r}$ denote the rightmost vertex in $V_{k-1} \cap B(v, C^*\delta^{k-2})$. There are two alternatives which determine our subcases.

Case F-T1: If $r = s$ or if $|w_{v,r} - w_{v,r+1}| \geq 30C^*\delta^{k-2}$, set $\Gamma_{k,v}^R = \{v\}$.

Case F-T2: If $|w_{v,r} - w_{v,r+1}| < 30C^*\delta^{k-2}$ (notice the implied existence of $w_{v,r+1}$) then v_1 exists by (V2), so it must be that $|v - v_1| \geq 30C^*\delta^{k-1}$. Set $\Gamma_{k,v}^R = B[k, v, v_1]$.

This completes the description of $\Gamma_{k,v}^R$. We define the left half, $\Gamma_{k,v}^L$, of $\Gamma_{k,v}$ symmetrically. Let

$\Gamma_k^{\text{Flat}} := \bigcup_{v \in V_k^{\text{Flat}}} \Gamma_{k,v}$. If $V_k^{\text{Non-flat}} = \emptyset$, set

$$\Gamma_k = \Gamma_k^{\text{Flat}} \cup \bigcup_{j=k_0}^{k-1} \bigcup_{B[j,w',w''] \subset \Gamma_j} B[j, w', w''];$$

the construction at stage k is complete. Otherwise, we will construct $\Gamma_{k,v}$ for $v \in V_k^{\text{Non-flat}}$. We will use these locally defined sets to define $\Gamma_k^{\text{Non-flat}}$ which will then be appended to Γ_k^{Flat} . The resulting set will be Γ_k .

Case N Construction

Fix $v \in V_k^{\text{Non-flat}}$. We first define $\Gamma_{k,v}$ in terms of a graph. Let $\mathcal{E}_{k,v}$ be the set of all edges $[v', v'']$ such that $[v', v'']$ is an edge in Γ_k^{Flat} or in S_k or $B[k, v', v'']$ is a bridge in Γ_k^{Flat} , and either v' or v'' is in $B(v, 33C^*\delta^{k-2})$. Let $\mathcal{V}_{k,v}$ be the set of vertices in $V_k \cap B(v, 33C^*\delta^{k-2})$ together with any additional endpoints of edges in $\mathcal{E}_{k,v}$. Let $G_{k,v}$ be the graph with edges set $\mathcal{E}_{k,v}$ and vertex set $\mathcal{V}_{k,v}$. If $G_{k,v}$ is connected then we let $\Gamma_{k,v}$ be the set with edges $[v', v'']$ or bridges $B[k, v', v'']$ such that $[v', v''] \in \mathcal{E}_{k,v}$. Otherwise, label the connected components of $G_{k,v} : G_{k,v}^{(1)}, \dots, G_{k,v}^{(n)}$. Each connected component contains at least one non-flat vertex, say v_i for $G_{k,v}^{(i)}$. Add edge $[v_i, v_{i+1}]$ to a new edge set, $\mathcal{E}'_{k,v}$, for $1 \leq i \leq n-1$. Then redefine $G_{k,v}$ to be the graph with edge set $\mathcal{E}_{k,v} \cup \mathcal{E}'_{k,v}$ and vertex set $\mathcal{V}_{k,v}$.

We now consider the global graph G'_k with edge set $\mathcal{E}'_k = \bigcup_{v \in V_k^{\text{Non-flat}}} \mathcal{E}'_{k,v}$ and vertex set $\mathcal{V}_k = \bigcup_{v \in V_k^{\text{Non-flat}}} \mathcal{V}_{k,v}$. If G'_k contains cycles, we remove edges from \mathcal{E}'_k one-by-one until no cycles remain. The resulting graph G'_k is a union of trees such that any two vertices which were originally connected are still connected. We define $\Gamma_k^{\text{Non-flat}}$ to be the set with edges $[v', v'']$ or bridges $B[k, v', v'']$ such that $[v', v''] \in \left(\bigcup_{v \in V_k^{\text{Non-flat}}} \mathcal{E}_{k,v} \right) \cup \mathcal{E}'_k$ and vertex set $\bigcup_{v \in V_k} \mathcal{V}_{k,v}$. When $|v' - v''| < 30C^*\delta^{k-1}$, we add the new edge $[v', v'']$ to $\text{Edge}(k)$ (this includes all edges from S_k) and when $|v' - v''| \geq 30C^*\delta^{k-1}$ we add the new bridge $B[k, v', v'']$ to $\text{Bridge}_{\text{Non-flat}}(k)$. Finally, we set

$$\Gamma_k = \Gamma_k^{\text{Flat}} \cup \Gamma_k^{\text{Non-flat}} \cup \bigcup_{j=k_0}^{k-1} \bigcup_{B[j, w', w''] \subset \Gamma_j} B[j, w', w''].$$

4.2 Connectedness

We will now prove that Γ_k is connected for each $k \geq k_0$. Again, we rely heavily on the proof of connectedness in [8]. We remark that the use of the exponent $k-1$ rather than k in the bound

distinguishing between edges and bridge for the case $\alpha_{k,v} < \epsilon$ follows from the use property (V2) in the proof of connectedness. We provide details of the proof to highlight where the smaller exponent is needed.

For $k \geq k_0$, every point $x \in \Gamma_k$ is connected to V_k in Γ_k because x belongs to an edge $[v', v'']$ between vertices $v', v'' \in V_k$ or to some bridge $B[j, u', u'']$ between vertices $u', u'' \in V_j$ for some $k_0 \leq j \leq k$. Thus, as in [8], to prove that Γ_k is a connected set, it suffices to prove that every pair of vertices in V_k is connected in Γ_k . We use a double induction scheme as in [8, Section 8.3] to prove that if for any $k \geq k_0 + 1$, if Γ_{k-1} is connected then Γ_k is connected.

Our initial induction is on k . For the base case, generation k_0 , we consider two cases. First suppose that $V_{k_0}^{\text{Flat}} \neq \emptyset$ or $V_{k_0}^{\text{Non-flat}}$ contains a semi-flat vertex. Then recall there exists a linear ordering on all points in V_{k_0} , $v_{-l}, \dots, v_0, \dots, v_m$, and Γ_{k_0} is constructed by connected by adding an edge $[v_i, v_{i+1}]$ for $-l \leq i \leq m - 1$. In particular, for $s > r$, v_r is connected to v_s by the sequence of edges $[v_r, v_{r+1}], \dots, [v_{s-1}, v_s]$. Suppose instead that $V_{k_0}^{\text{Flat}} = \emptyset$ and $V_{k_0}^{\text{Non-flat}}$ does not contain any semi-flat vertex. Then Γ_{k_0} is defined to be a connected graph on the vertices in V_{k_0} so the result holds trivially.

Next suppose that Γ_{k-1} is connected for some $k \geq k_0 + 1$. Note that it follows trivially from construction in both the flat case and the non-flat case that if $v', v'' \in V_k$ and $|v' - v''| < 30C^* \delta^{k-1}$, then v' and v'' are connected in Γ_k . Let x and y be arbitrary vertices in V_k and let $w_x, w_y \in V_{k-1}$ denote vertices that are closest to x and y respectively. Since V_{k-1} is connected, w_x and w_y can be joined in Γ_{k-1} by a tour of $p + 1$ vertices in V_{k-1} , say,

$$w_0 = w_x, w_1, w_2, \dots, w_p = w_y$$

where each pair w_i, w_{i+1} of consecutive vertices is connected in Γ_{k-1} by an edge $[w_i, w_{i+1}]$ or by a bridge $B[j, u', u'']$ for some $k_0 \leq j \leq k - 1$ and $u', u'' \in V_j$ with the property that $w_i \in e[j, u]$

and $w_{i+1} \in e[j, u]$. Set $v_0 = x$. By (V3) and the choice of w_0 to be a closest point to x , we have, $|v_0 - w_0| = |x - w_x| < C^* \delta^k$.

We now begin our second induction. For any $0 \leq t \leq p-1$ there exists a vertex $v_t \in V_k$ such that $|v_t - w_t| < C^* \delta^{k-1}$ by (V2). Assume that v_0 and v_t are connected in Γ_k . If $t \leq p-2$, choose the vertex v_{t+1} to be any vertex in V_k satisfying $|v_{t+1} - w_{t+1}| < C^* \delta^{k-1}$; such vertex exists by (V2). Otherwise, if $t = p-1$, set $v_{t+1} = v_p = y$, which of course satisfies $|v_{t+1} - w_{t+1}| = |y - w_y| < C^* \delta^k < C^* \delta^{k-1}$ by (V3) and by choice of w_y as the closest vertex in V_{k-1} . We will show that v_t and v_{t+1} are connected in Γ_k in order to conclude that v_0 and v_{t+1} are connected in Γ_k . We consider two cases:

1. w_t and w_{t+1} are connected by a bridge.
2. w_t and w_{t+1} are connected by an edge.

First suppose that w_t and w_{t+1} are connected by a bridge $B[j, u', u'']$ for $u', u'' \in V_j$ where $k_0 \leq j \leq k-1$. Without loss of generality, suppose $w_t \in e[j, u']$ and $w_{t+1} \in e[j, u'']$. Let z' denote the point in $V_k \cap e[j, u']$ and z'' denote the point in $V_k \cap e[j, u'']$. Since $z', z'' \in B[j, u', u''] \subset \Gamma_k$ and bridges are connected subsets of Γ_k , z' and z'' are connected in Γ_k . Now by definition of extension in terms of nearest points and by (V2), $|z' - w_t| < C^* \delta^{k-1}$. Thus

$$|v_t - z'| \leq |v_t - w_t| + |w_t - z'| < 2C^* \delta^{k-1} < 30C^* \delta^{k-1}.$$

An analogous estimation show that $|v_{t+1} - z''| < 30C^* \delta^{k-1}$. It follows that v_t is connected to z' and v_{t+1} is connected to z'' so v_t is connected to v_{t+1} in Γ_k .

Secondly, suppose that $[w_t, w_{t+1}]$ is an edge in Γ_{k-1} . By definition of edge, we know that

$|w_t - w_{t+1}| < 30C^*\delta^{k-2}$. Hence

$$|v_t - v_{t+1}| \leq |v_t - w_t| + |w_t - w_{t+1}| + |w_{t+1} - v_{t+1}| \leq 2C^*\delta^{k-1} + 30C^*\delta^{k-2} < 32C^*\delta^{k-2}.$$

To conclude the proof of the connectedness, we consider two cases depending on whether $\alpha_{k,v_t} < \epsilon$ or $\alpha_{k,v_t} \geq \epsilon$. When $\alpha_{k,v_t} \geq \epsilon$, we are in the **Case N** construction of Γ_k . In this case, we defined Γ_{k,v_t} to be a connected graph with vertices in $B(v_t, 33C^*\delta^{k-2})$ so, in particular, v_t is connected to v_{t+1} in Γ_{k,v_t} . The reduction of edges to construct $\Gamma_k^{\text{Non-flat}}$ did not affect connectedness.

On the other hand, when $\alpha_{k,v_t} \leq \epsilon$ the vertices in $V_k \cap B(v_t, 33C^*\delta^{k-2})$ can be arranged linearly according to the relative ordering under orthogonal projection onto $\ell_{k,v}$. We label the vertices in $V_k \cap B(v_t, 32C^*\delta^{k-2})$ lying between v_t and v_{t+1} according to that ordering,

$$z_0 = v_t, z_1, \dots, z_q = v_{t+1}.$$

Since $(1+3\epsilon^2)32 < 33$, Lemma 4.0.2 guarantees that $v_t, v_{t+1} \in B(z_i, 33C^*\delta^{k-2})$ for all $1 \leq i \leq q$. Suppose that $\alpha_{k,z_i} < \epsilon$ for all $0 \leq i \leq q$. Since Γ_{k-1} contains the edge $[w_t, w_{t+1}]$, the set Γ_{k,z_i} contains either a bridge $B[k, z_i, z_{i+1}]$ or an edge $[z_i, z_{i+1}]$ for each $0 \leq i \leq q-1$ depending on whether z_i is terminal or not terminal to z_{i+1} . (We emphasize that **Case F T1** does not occur here since w_{t+1} exists.) Hence z_i and z_{i+1} are connected for all $0 \leq i \leq q-1$. By concatenating paths, we see that $v_t = z_0$ and $v_{t+1} = z_q$ are connected in Γ_k as well. Suppose instead that there exists some i such that $\alpha_{k,z_i} \geq \epsilon$. Then again by the **Case N** construction of Γ_{k,z_i} as a connected graph, z_0 is connected to z_q , i.e. v_t is connected to v_{t+1} .

By induction, v_0 and v_t are connected in Γ_k for all $1 \leq t \leq p$. In particular, we note that $x = v_0$ and $y = v_p$ are connected in Γ . Since x and y are arbitrary in V_k , it follows that V_k is connected in Γ_k . Again by induction, Γ_k is connected for all $k > k_0$.

4.3 Length estimates

The goal of this section is to find length estimates for Γ_k , $k \geq k_0$ which then provide the desired bound for the length of the limiting curve Γ . We first bound the length of Γ_{k_0} either in terms of $C^* \delta^{k_0}$ or by the sum over $\alpha_{k_0, v}$ over $v \in V_{k_0}$. We then bound $\mathcal{H}^1(\Gamma_k)$ by $\mathcal{H}^1(\Gamma_{k-1}) + C \sum_{v \in V_k} \alpha_{k, v}^2 \delta^k$ for all $k \geq k_0 + 1$ where C is independent of k . We follow the outline of [8] and indicate changes required, particularly near vertices $v \in V^{\text{Non-flat}}(k)$ and for the **Case F-NT** construction. Before we begin the estimates, we introduce the notion of “phantom length.”

Phantom length

As in [8], we will use phantom length to overcome the challenge of terminal vertices where the old curve does not span the new curve. We define phantom length analogously to the definition in [8, Section 9.1]; we provide the following exposition in order to introduce terminology that will be used in later estimates.

To begin we establish notation that will allow us to refer to specific vertices in the extensions of a bridge. For each extension $e[k, v]$, say

$$e[k, v] = \overline{\bigcup_{i=1}^{\infty} [v_i, v_{i+1}]}$$

define the corresponding extension index set $I[k, v]$ by

$$I[k, v] = \{(k + i, v_i), i \geq 1\}.$$

Then for each bridge, $B[k, v', v'']$, we define the corresponding bridge index set $I[k, v', v'']$ by

$$I[k, v', v''] = I[k, v'] \cup I[k, v''].$$

For all generations $k \geq k_0$ and for all vertices $v \in V_k$, we define that phantom length $p_{k,v} := 3C^* \delta^{k-1}$. In particular, for a $B[k, v', v'']$ between vertices $v', v'' \in V_k$ the totality $p_{k,v',v''}$ of phantom length associated to the index set is

$$p_{k,v',v''} := 3C^* \sum_{i=0}^{\infty} \delta^{k+i-1} + 3C^* \sum_{j=0}^{\infty} \delta^{k+j-1} < 12C^* \delta^{k-1}$$

We track phantom length in pairs (k, v) so that we can record both the location and length of the phantom length. We initialize $\text{Phantom}(k_0)$ to be

$$\text{Phantom}(k_0) := \{(k_0, v) : v \in V_{k_0}\}.$$

Now suppose that $\text{Phantom}(k_0), \dots, \text{Phantom}(k-1)$ have been defined for each $k \geq k_0 + 1$ so that $\text{Phantom}(k-1)$ satisfies the following two properties:

1. **Bridge Property:** If a bridge $B[k-1, w', w'']$ is included in Γ_{k-1} then $\text{Phantom}(k-1)$ contains $I[k-1, w', w'']$.
2. **Terminal Vertex Property:** Let $w \in V_{k-1}$ be a terminal vertex, and let ℓ be a line such that $\text{dist}(y, \ell) < \epsilon \delta^{k-1}$ for all $y \in V_{k-1} \cap B(w, 30C^* \delta^{k-2})$. Arrange $V_{k-1} \cap B(w, 30C^* \delta^{k-2})$ linearly with respect to the orthogonal projection π_ℓ onto ℓ . If there is no vertex to the “left” of w or to the “right” of w , then $(k-1, w) \in \text{Phantom}(k-1)$.

Note that $\text{Phantom}(k_0)$ satisfies the Bridge Property trivially since no bridges are added during the initial stage of construction and satisfies the Terminal Vertex Property trivially since $\text{Phantom}(k_0)$ includes (k_0, v) for every $v \in V_{k_0}$. We use $\text{Phantom}(k-1)$ as a basis for defining $\text{Phantom}(k)$. In particular, we initialize $\text{Phantom}(k)$ by setting it to $\text{Phantom}(k-1)$. Next, we delete all pairs of the form $(k-1, w)$ or (k, \tilde{v}) that appear in $\text{Phantom}(k-1)$ from $\text{Phantom}(k)$. Finally, for each

vertex $v \in V_k$, we include additional pairs in $\text{Phantom}(k)$ according to the following rules:

Case F-NT: If $\alpha_{k,v} < \epsilon$ and $\Gamma_{k,v}^R$ and $\Gamma_{k,v}^L$ are both defined using **Case F-NT** then (k, v) does not generate any new phantom length.

Case F-T1: If $\alpha_{k,v} < \epsilon$ and either $\Gamma_{k,v}^R$ or $\Gamma_{k,v}^L$ is defined by **Case F-T1** then include $(k, v) \in \text{Phantom}(k)$.

Case F-T2: Suppose $\alpha_{k,v} < \epsilon$ and either $\Gamma_{k,v}^R$ or $\Gamma_{k,v}^L$ is defined using **Case F-T2**. When $\Gamma_{k,v}^R$ is defined by **Case F-T2**, include $I[k, v, v_1]$ as a subset of $\text{Phantom}(k)$. When $\Gamma_{k,v}^L$ is defined by **Case F-T2**, include $I[k, v_{-1}, v]$ as a subset of $\text{Phantom}(k)$. In particular, in either case (k, v) is included in $\text{Phantom}(k)$.

Case N: If $\alpha_{k,v} \geq \epsilon$, include (k, v') in $\text{Phantom}(k)$ for all vertices $v' \in V_k^{\text{Non-flat}} \cap B(v, 33C^*\delta^{k-2})$. Additionally, include $I[k, v', v'']$ as a subset of $\text{Phantom}(k)$ for every bridge $B[k, v', v'']$ in $\Gamma_{k,v}$.

Clearly, $\text{Phantom}(k)$ satisfies the bridge property. To check that $\text{Phantom}(k)$ satisfies that terminal vertex property, let $v \in V_k$ be a terminal vertex, and suppose that we can find a line ℓ such that

$$\text{dist}(y, \ell) < \epsilon\delta^k \text{ for all } y \in V_k \cap B(v, 30C^*\delta^{k-1}).$$

Identify ℓ with \mathbb{R}^n and arrange $V_k \cap B(v, 30C^*\delta^{k-1})$ linearly with respect to the orthogonal projection π_ℓ onto ℓ . Assume there is no vertex $v' \in V_k \cap B(v, 30C^*\delta^{k-1})$ to the “left” of v or to the “right” of v with respect to the ordering under π_ℓ . If $\alpha_{k,v} \geq \epsilon$, then (k, \tilde{v}) was included in $\text{Phantom}(k)$ for every $\tilde{v} \in V_k^{\text{Non-flat}} \cap B(v, 33C^*\delta^{k-2})$. In particular, (k, v) is in $\text{Phantom}(k)$. Otherwise $\alpha_{k,v} < \epsilon$, so $V_k \cap B(v, 30C^*\delta^{k-1})$ is also linearly ordered with respect to orthogonal projection onto $\ell_{k,v}$. By Lemma 4.0.2, the orderings agree modulo the choice of orientation for the lines. The assumption that there is no vertex $v' \in V_k \cap B(v, 30C^*\delta^{k-1})$ to the “left” or to the “right” translates to the statement that $\Gamma_{k,v}^L$ or $\Gamma_{k,v}^R$ is defined by **Case F-T1** or **Case F-T2**, so (k, v) was included in $\text{Phantom}(k)$. Therefore, $\text{Phantom}(k)$ satisfies the terminal vertex property.

Cores of Bridges

For each bridge $B[k, v', v''] \in \text{Bridge}_{\text{Flat}}(k)$ between vertices $v', v'' \in V_k$, we define the core $C[k, v', v'']$ of the bridge to be

$$C[k, v', v''] := \frac{9}{10}[v', v'']$$

i.e., $C[k, v', v'']$ is the interval of length $\frac{9}{10}$ of the length of $[v', v'']$ that is concentric to $[v', v'']$.

Recall that $\mathcal{H}^1(B[k, v', v'']) \geq 30C^*\delta^{k-1}$ for every bridge $B[k, v', v''] \in \text{Bridge}_{\text{Flat}}(k)$. Thus the corresponding core also has significant length,

$$\mathcal{H}^1(C[k, v', v'']) \geq 27C^*\delta^{k-1}.$$

Cores in $\text{Cores}_{\text{Flat}}(k)$ are disjoint; see [8, Section 9.2]. We emphasize that here we only define the cores for bridges in $\text{Bridge}_{\text{Flat}}(k)$

Proof of Theorem C

To establish Theorem C, it suffices to prove that

$$\sum_{[v', v''] \in \text{Edge}(k_0)} \mathcal{H}^1([v', v'']) + \sum_{(j, u) \in \text{Phantom}(k_0)} p_{j, u} \leq C\delta^{k_0} + \sum_{v \in V_0} \alpha_{k_0, v} \delta^{k_0}, \quad (4.3.1)$$

and then that for all $k \geq k_0 + 1$

$$\begin{aligned} & \sum_{[v', v''] \in \text{Edges}(k)} \mathcal{H}^1([v', v'']) + \sum_{B[k, v', v''] \in \text{Bridge}(k)} \mathcal{H}^1(B[k, v', v'']) + \sum_{(j, u) \in \text{Phantom}(k)} p_{j, u} \\ & \leq \sum_{[w', w''] \in \text{Edges}(k-1)} \mathcal{H}^1([w', w'']) + \sum_{(j, u) \in \text{Phantom}(k-1)} p_{j, u} \\ & \quad + C \sum_{v \in V_k} \alpha_{k, v}^2 \delta^k + \frac{25}{27} \sum_{C[k, v', v''] \in \text{Cores}_{\text{Flat}}(k)} \mathcal{H}^1([k, v', v'']), \end{aligned} \quad (4.3.2)$$

where C denotes a constant depending only on C^* and δ . To see that establishing these bounds is sufficient, iterate (4.3.2) $k - k_0$ times and then apply (4.3.1). See [8, Section 9.3] for details.

Preliminary Observation

We begin with a preliminary observation about the lengths of edges and bridges that will be used in the proofs of the two inequalities. Recall that an edge $[v', v'']$ in the curves $\Gamma_{k_0}, \Gamma_{k_0+1}, \dots$ is included for some $v', v'' \in V_k$ only if $|v' - v''| < 30C^*\delta^{k-1}$, while a bridge $B[k, v', v''] \in \text{Bridge}(k)$ is included for some $v', v'' \in V_k$ only if $30C^*\delta^{k-1} \leq |v' - v''| \leq 66C^*\delta^{k-2}$. Furthermore, the lengths of the extensions are controlled by (V2): For all $k \geq k_0$ and $v \in V_k$, $\mathcal{H}^1(e[k, v]) \leq 2C^*\delta^k$. Thus, if $B[k, v', v''] \in \text{Bridge}(k)$ then

$$\begin{aligned} \mathcal{H}^1(B[k, v', v'']) &\leq \mathcal{H}^1(e[k, v']) + \mathcal{H}^1([v', v'']) + \mathcal{H}^1(e[k, v'']) \\ &\leq 4C^*\delta^{k-2} + \mathcal{H}^1([v', v'']) \leq \frac{4\delta^2 + 30}{30} \mathcal{H}^1([v', v'']) < \frac{32}{30} \mathcal{H}^1([v', v'']). \end{aligned}$$

Length Estimates for Base Case k_0

Recall that there are no bridges added during the construction of Γ_{k_0} . Since $\mathcal{H}^1([v', v'']) \leq 30C^*\delta^{k_0-1}$ for every $[v', v''] \in \text{Edge}(k_0)$,

$$\sum_{[v', v''] \in \text{Edge}(k_0)} \mathcal{H}^1([v', v'']) \leq \#V_{k_0} 30C^*\delta^{k_0-1}. \quad (4.3.3)$$

Additionally

$$\sum_{(j, u) \in \text{Phantom}(k_0)} p_{j, u} = \sum_{v \in V_{k_0}} p_{k_0, v} \leq \#V_{k_0} 3C^*\delta^{k_0-1}. \quad (4.3.4)$$

Now we consider two cases. Suppose first that $V_{k_0}^{\text{Flat}} \neq \emptyset$. Fix v_0 such that $\alpha_{k_0, v_0} < \epsilon$, and

consider the corresponding approximating line ℓ_{k_0, v_0} . For any $v_1, v_2 \in V_{k_0}$, consider $\pi(v_1), \pi(v_2)$, their respective projections onto ℓ_{k_0, v_0} . We have

$$|\pi(v_1) - \pi(v_2)| \geq |v_1 - v_2| - \text{dist}(v_1, \ell_{k_0, v_0}) - \text{dist}(v_2, \ell_{k_0, v_0}) \geq C^* \delta^{k_0} - 2C^* \epsilon \delta^{k_0} > (1 - 3\epsilon) C^* \delta^{k_0}.$$

Since $\pi(v_i) \in B(v_0, 66C^* \delta^{k_0-2})$ we see that $\#V_0 \lesssim_{C^*, \delta} 1$. In particular,

$$\sum_{[v', v''] \in \text{Edge}(k_0)} \mathcal{H}^1([v', v'']) + \sum_{(j, u) \in \text{Phantom}(k_0)} p_{j, u} \lesssim_{C^*, \delta} \delta^{k_0}.$$

Alternatively, suppose that $V^{\text{Flat}}(k_0) = \emptyset$. Then for each added line segment in Γ_{k_0} , the length of the line segment is charged against the large $\alpha_{k_0, v}$ value for a unique $v \in V^{\text{Non-flat}}(k)$. We also charge the phantom length assigned at each vertex v to the large $\alpha_{k_0, v}$ value. That is,

$$\sum_{[v', v''] \in \text{Edge}(k_0)} \mathcal{H}^1([v', v'']) + \sum_{(j, u) \in \text{Phantom}(k_0)} p_{j, u} \lesssim_{C^*, \delta} \sum_{v \in V_{k_0}} \alpha_{k_0, v} \delta^{k_0},$$

Combining these two estimates we conclude that inequality (4.3.1) holds.

Length Estimates for $k > k_0$

We are now ready to work on the proof of (4.3.2). Note that edges and bridges forming the curve Γ_k and “new” phantom length may appear in the local portion of Γ_k near v , namely $\Gamma_{k, v}$, for several vertices $v \in V_k$ but only need to be accounted for once each in order to estimate the left hand side of (4.3.2). We will present the length estimates for **Case N** construction first and then we will present estimates for **Case F** construction. We will refer readers to [8, Section 9.5] for some details of the **Case F** construction estimates.

Case N: Here we will pay of edges or bridges in $\Gamma_k \setminus \Gamma_k^{\text{Flat}}$ as well as well as any parts of edges

in $B(v, 2C^*\delta^{k-1})$ for $v \in V_k^{\text{Non-flat}}$ that were added during a **Case F** stage of construction. We will charge the length to the large $\alpha_{k,v}$ value corresponding to vertices $v \in V_k$. By Lemma 4.0.2, for a semi-flat vertex $v \in V_k^{\text{Non-flat}}$, the sum of the length of edges in S_k associated to vertex v cannot exceed

$$66(1 + 3\epsilon^2)C^*\delta^{k-1} < 67C^*\delta^{k-1} \leq \left(\frac{67C^*}{\epsilon}\right)\alpha_{k,v}\delta^{k-1}.$$

Additionally, since G'_k is a union of disjoint trees, each edge $[v, v']$ in G'_k can be assigned uniquely to a vertex, say $v \in V_k^{\text{Non-flat}}$. Then since $\alpha_{k,v} \geq \epsilon$, if the corresponding edge $[v, v']$ was added to $\Gamma_k^{\text{Non-flat}}$ then $\mathcal{H}^1([v, v']) \leq 30C^*\epsilon^{-1}\alpha_{k,v}\delta^{k-1}$. If instead the corresponding bridge $B([v, v', k])$ was added in the construction of $\Gamma_k^{\text{Non-flat}}$ then

$$\mathcal{H}^1(B[v, v', k]) \leq \left(\frac{32}{30}\right)66C^*\delta^{k-2},$$

so $\mathcal{H}^1(B[v, v', k]) \leq 71C^*\epsilon^{-1}\alpha_{k,v}\delta^{k-2}$. Finally, the length of parts of edges in $B(v, 2C^*\delta^{k-1})$ added during a **Case F** stage of construction is at most $(1+3\epsilon^2)4C^*\delta^k \leq 5C^*\delta^{k-1}$. Let $\text{Edge}_{\text{Non-flat}}(k)$ denote the set of edges in $E(k)$ such that $[v', v''] \in \mathcal{E}'_k$ or $[v', v''] \in S_k$. Then

$$\begin{aligned} & \left(\sum_{[v', v''] \in \text{Edge}_{\text{Non-flat}}(k)} \mathcal{H}^1([v', v'']) + \sum_{B([v', v'', k]) \in \text{Bridge}_{\text{Non-flat}}(k)} \mathcal{H}^1(B[v', v'', k]) + 5C^*\delta^{k-1} \right) \\ & \lesssim_{C^*, \delta} \sum_{v \in V_k^{\text{Non-flat}}} \alpha_{k,v}^2 \delta^k. \end{aligned} \tag{4.3.5}$$

We emphasize that here we rely on the fact that we constructed G'_k to be the union of trees, so we can charge each edge of \mathcal{E}'_k to a unique vertex $v \in V_k^{\text{Non-flat}}$. We also bound the phantom length as

follows

$$\begin{aligned}
& \sum_{v \in V_k^{\text{Non-flat}}} \left(p_{k,v} + \sum_{B[v',v'',k] \in \text{Bridge}_{\text{Non-flat}}(k,v)} p_{k,v',v''} \right) \\
& \leq \sum_{v' \in V_k^{\text{Non-flat}}} \left(3C^* \delta^{k-1} + \sum_{\text{Bridge}[v',v'',k] \in \text{Bridge}_{\text{Non-flat}}(k,v)} 12C^* \delta^{k-1} \right) \lesssim_{C^*,\delta} \sum_{v \in V_k^{\text{Non-flat}}} \alpha_{k,v}^2 \delta^k.
\end{aligned}$$

Case F-T1: This estimate follows identically to as in Section 9.5 of [8]. In particular,

$$p_{k,v} + \sum_{[v',v''] \in \text{Edges}(k)} \mathcal{H}^1([v',v] \cap B(v, 2C^* \delta^k)) \leq p_{k-1,w_{v,r}}.$$

Case F-T2: Suppose v is terminal to the right with alternative T2. Recall that in this step we need to add a bridge in $\text{Bridge}_{\text{Flat}}(k)$. Write $v_1 \in V_k$ and $w_{v,r}, w_{v,r+1} \in V_{k-1}$ for the vertices appearing in the definition of $\Gamma_{k,v}^R$. In this case, we will pay for p_{k,v,v_1} , the length of the bridge $B[k, v, v_1]$, and the length of the edges in $\Gamma_k \cap B(v, 2C^* \delta^{k-1})$. We will also pay for the length in $\Gamma_k \cap B(v_1, 2C^* \delta^{k-1})$ if we have not already done so. As previously noted,

$$\mathcal{H}^1(B[k, v, v_1]) \leq 4C^* \delta^k + \mathcal{H}^1([v', v'']),$$

Since $|v - w_{v,r}| < 2C^* \delta^k$ and $|v_1 - w_{v,r+1}| < 2C^* \delta^{k-1}$, it follows that

$$\mathcal{H}^1(B[k, v, v_1]) \leq 4C^* \delta^{k-1} + \mathcal{H}^1([v, v_1]) \leq 8C^* \delta^{k-1} + \mathcal{H}^1([w_{v,r}, w_{v,r+1}]).$$

Note that if $w_{v,r} \notin V_{k-1}^{\text{Flat}}$ then $w_{v,r}$ is a semi-flat vertex. In either case, the edge $[w_{v,r}, w_{v,r+1}]$ is in Γ_{k-1} . Additionally, the totality of phantom length associated with vertices in $B[k, v, v_1]$ is

$12C^*\delta^{k-1}$. Unlike in [8, Section 9.5], we cannot assume $\alpha_{k,v_1} < \epsilon$. However, if $\alpha_{k,v_1} \geq \epsilon$ then we have already paid for the length of $\Gamma_k \cap B(v_1, 2C^*\delta^k)$. In this case,

$$\begin{aligned} & \mathcal{H}^1(B[k, v, v_1]) + p_{k,v,v_1} + \sum_{[v',v''] \in \text{Edges}(k)} \mathcal{H}^1([v', v''] \cap B(v, 2C^*\delta^k)) \\ & \leq \mathcal{H}^1([w_{v,r}, w_{v,r+1}]) + 23C^*\delta^{k-1} \\ & \leq \mathcal{H}^1([w_{v,r}, w_{v,r+1}]) + \frac{23}{27}\mathcal{H}^1(C[k, v, v_1]) \end{aligned}$$

where $[w_{v,r}, w_{v,r+1}] \in \text{Edges}(k-1)$ and $C[k, v, v_1] \in \text{Cores}_{\text{Flat}}(k)$. Otherwise, $\alpha_{k,v_1} < \epsilon$, and the total length of parts of edges in $\Gamma_k \cap B(v, 2C^*\delta^{k-1}) \cup B(v_1, 2C^*\delta^{k-1})$ which has not yet been paid for does not exceed $5C^*\delta^{k-1}$ by Lemma 4.0.2. Altogether these estimates sum to give the bounds

$$\begin{aligned} & \mathcal{H}^1(B[k, v, v_1]) + p_{k,v,v_1} + \sum_{[v',v''] \in \text{Edges}(k)} \mathcal{H}^1([v', v''] \cap B(v, 2C^*\delta^k) \cup B(v_1, 2C^*\delta^k)) \\ & \leq \mathcal{H}^1([w_{v,r}, w_{v,r+1}]) + 25C^*\delta^{k-1} \\ & \leq \mathcal{H}^1([w_{v,r}, w_{v,r+1}]) + \frac{25}{27}\mathcal{H}^1(C[k, v, v_1]) \end{aligned}$$

where $[w_{v,r}, w_{v,r+1}] \in \text{Edges}(k-1)$ and $C[k, v, v_1] \in \text{Cores}_{\text{Flat}}(k)$.

Case F-NT: Let $[v', v'']$ be an edge between vertices $v', v'' \in V_k$ which are not yet wholly paid for. Then there exists a vertex $v \in V_k^{\text{Flat}}$ such that $|v - v'| < 30C^*\delta^{k-1}$, $|v - v''| < 30C^*\delta^{k-1}$, $|v' - v''| < 30C^*\delta^{k-1}$, and v' is immediately to the left (or to the right) of v'' relative to the order defined by $\ell_{k,v}$. Let $[u', u'']$ be the largest closed subinterval of $[v', v'']$ such that u' and u'' lie a distance at least $2C^*\delta^{k-1}$ away from **Case F-T1** and **Case F-T2** vertices as well as vertices in $V_k^{\text{Non-flat}}$. Note that we already paid for the length within distance $2C^*\delta^{k-1}$ of these three types of

vertices. Applying Lemma 4.0.2,

$$\begin{aligned}\mathcal{H}^1([u', u'']) &\leq (1 + 3\alpha_{k,v'}^2)\mathcal{H}^1([\pi_{k,v'}(u'), \pi_{k,v'}(u'')]) \\ &= \mathcal{H}^1([\pi_{k,v'}(u'), \pi_{k,v'}(u'')]) + 90C^*\alpha_{k,v}^2\delta^{k-1}.\end{aligned}$$

Without loss of generality, suppose that u' lies to the left of u'' relative to the order of their respective projections on $\ell_{k,v'}$. Let z' denote the first vertex in $V_k \cap B(v', 33C^*\delta^{k-2})$ to the left of u' , relative to the order of their projection onto $\ell_{k,v}$, such that $\pi_{k,v'}(z') < \pi_{k,v}(u') - C^*\delta^k$. Analogously, let z'' denote the first vertex in $V_k \cap B(v, 33C^*\delta^{k-2})$ to the right of u'' , such that $\pi_{k,v}(u'') + C^*\delta^k < \pi_{k,v}(z'')$. The vertex z' as described above always exists since, if $z' \neq v'$ then $|v' - u'| \leq C^*\delta^k$. Thus v' must be a **Case F-NT** vertex; a similar conclusion holds for v'' . This implies that $|z' - v'| < 30C^*\delta^{k-1}$ and $|z'' - v''| < 30C^*\delta^{k-1}$. By (V3), we can find $w', w'' \in V_{k-1}$ such that $|w' - z'| < C^*\delta^k$ and $|w'' - z''| < C^*\delta^k$. By choice of w' and w'' ,

$$\pi_{k,v'}(w') < \pi_{k,v'}(u') < \pi_{k,v''}(u'') < \pi_{k,v'}(w'').$$

We claim that there exists a sequence of edges in Γ_{k-1} connecting w' to w'' such that the edges are contained in an $C^*\delta^k\epsilon$ -neighborhood of $\ell_{k,v}$. To see that this claim is true, recall that by (V3) there are $y', y'' \in V_{k-1}$ such that $|y' - v'| < C^*\delta^k$ and $|y'' - v''| < C^*\delta^{k-1}$. If $\alpha_{k-1,y'} < \epsilon$, then there exists an ordering on the points in $V_{k-1} \cap B(y', 66C^*\delta^{k-1})$ given by projection onto $\ell_{k-1,y'}$. In this case $|w' - y'| \leq |w' - z'| + |z' - v'| + |v' - y'| < 30C^*\delta^{k-2}$, so a sequence of edges between w' and y' was added during a **Case F-NT** stage of construction of Γ_{k-1} . A similar estimation shows that $|y' - y''| < 30C^*\delta^{k-2}$ so there is sequence of edges between y' and y'' . If instead $\alpha_{k-1,y'} \geq \epsilon$, then y' is a semi-flat vertex, and, by Lemma 4.0.2, the same sequence of edges was added to Γ_{k-1} in the **Case N** construction. Now y'' satisfies $\alpha_{k-1,y''} < \epsilon$ or y'' is a semi-flat vertex. In either

case, since $|y'' - w''| < 30C^*\delta^{k-2}$, there is a sequence of edges connecting y'' to w'' in Γ_{k-1} . We emphasize that since $|w' - v| < 66C^*\delta^{k-2}$ and $|w'' - v| < 66C^*\delta^{k-2}$, the edges added during the construction of Γ_{k-1} agree with ordering of points according to projection onto $\ell_{k,v}$. Furthermore, since all $x \in V_{k-1} \cap B(v, 66C^*\delta^{k-2})$ are distance less than $C^*\delta^k\epsilon$ away from $\ell_{k,v}$, the portion of Γ_{k-1} between w' and w'' is distance less than $C^*\delta^k\epsilon$ from $\ell_{k,v}$.

We can pay for $\mathcal{H}^1([\pi_{k,v'}(u'), \pi_{k,v'}(u'')])$ using the portion of edges in the curve $\Gamma_{k-1} \cap B(v, 66C^*\delta^{k-2})$ that lies over the segment $[\pi_{k,v}(u'), \pi_{k,v}(u'')]$. Thus,

$$\mathcal{H}^1([u', u'']) \leq \mathcal{H}^1(E_{k-1}(v) \cap \pi_{k,v}^{-1}([\pi_{k,v}(u'), \pi_{k,v}(u'')])) + 90C^*\alpha_{k,v}^2\delta^{k-1}$$

where $E_{k-1}(v)$ denotes the union of edges in Γ_{k-1} between the vertices in $V_{k-1} \cap B(v, 66C^*\delta^{k-2})$.

It remains to estimate the overlap of the sets of the form

$$S_{k,v}[u', u''] := E_{k-1}(v) \cap \pi_{k,v}^{-1}([\pi_{k,v}(u'), \pi_{k,v}(u'')])$$

Since $S_{k,v'}([u', u'']) \subset S_{k,v'}([v', v''])$, it suffices to estimate the length of the overlap of sets $S_{k,v'}[v', v'']$. Suppose that v_1, v_2, v_3 are consecutive vertices in $V_k \cap B(v^{(1)}, 66C^*\delta^{k-2})$ such that portions of edges $[v_1, v_2]$ and $[v_2, v_3]$ are being paid for in this **Case F-NT** stage. Suppose that that $[v_1, v_2]$ was added during the construction of $\Gamma_{k,v^{(1)}}$ and $[v_2, v_3]$ was added during the construction of $\Gamma_{k,v^{(2)}}$ where $v^{(1)}, v^{(2)} \in V_k^{\text{Flat}}$ are both non-terminal. We will show that

$$\mathcal{H}^1(S_{k,v^{(1)}}[v_1, v_2] \cap S_{k,v^{(2)}}[v_2, v_3]) < 40\alpha^2\delta^{k-1}$$

where $\alpha = \max\{\alpha_{k,v^{(1)}}, \alpha_{k,v^{(2)}}\}$. To start, let ℓ_1 be a line which is parallel to $\ell_{k,v^{(1)}}$ but passes through v_2 , and similarly let ℓ_2 be a line which is parallel to $\ell_{k,v^{(2)}}$ and passes through v_2 . Let π_i denote orthogonal projection onto ℓ_i and let N_i denote the closed tubular neighborhood of ℓ_i of

radius $2\alpha\delta^k$. Also, let $E_{k-1}(v^{(1)}, v^{(2)}) := E_{k-1}(v^{(1)}) \cap E_{k-1}(v^{(2)})$. Then

$$\begin{aligned} S_{k,v^{(1)}}[v_1, v_2] \cap S_{k,v^{(2)}}[v_2, v_3] &\subset E_{k-1}(v^{(1)}, v^{(2)}) \cap \pi_1^{-1}([\pi_1(v_1), \pi_i(v_2)]) \cap N_1 \cap \pi_2^{-1}([\pi_2(v_2), \pi_2(v_3)]) \cap N_2 \\ &=: E_{k-1}(v^{(1)}, v^{(2)}) \cap S. \end{aligned}$$

The remainder of the overlap estimate follows identically as in [8, Section 9.5]. Now we combine all the estimates above to conclude (4.3.2).

Chapter 5

Graph rectifiable measures

In this chapter we prove Theorem D. Throughout H denotes a finite or infinite dimensional Hilbert space. Recall that we define the *good cone* at x with respect to V and α by

$$C_G(x, V, \alpha) := \{y \in H : \text{dist}(y - x, V) \leq \alpha|x - y|\},$$

and the bad cone at x with respect to V and α by

$$C_B(x, V, \alpha) := H \setminus C_G(x, V, \alpha).$$

We begin by collecting some geometric results that will be useful in the proof of Theorem D. The first result can be found in [26]. We present the proof, with slight modifications to highlight some important consequences.

Theorem 5.0.1 (Geometric Lemma). *Let $F \subset H$, let V be an m -dimensional linear plane in H ,*

and let $\alpha \in (0, 1)$. If

$$F \setminus C_{\mathcal{G}}(x, V, \alpha) = \emptyset \text{ for all } x \in F$$

then F is contained in an m -Lipschitz graphs. In particular, $F \subset \Gamma$ where Γ is a Lipschitz graph with respect to V and the Lipschitz constant corresponding to Γ is at most $1 + 1/(1 - \alpha^2)^{1/2}$.

Proof. Let $x \in F$. Let $P_V : H \rightarrow V$ denote standard projection onto the m -plane V . Suppose that $|P_V x - P_V y| < (1 - \alpha^2)^{1/2}|x - y|$. Then $y \in C_{\mathcal{B}}(x, V, \alpha)$, and by assumption of F this means that $y \notin F$. Thus we may assume that if $x, y \in F$ then

$$|P_V x - P_V y| \geq (1 - \alpha^2)^{1/2}|x - y|.$$

From this inequality we see that $P_V|_F$ is one-to-one with Lipschitz inverse $f = (P_V|_F)^{-1}$ and $Lip(f) \leq (1 - \alpha^2)^{-1/2}$. Note that $F = f(P_V|_F)$. Then there exists a Lipschitz extension $\tilde{f} : V \rightarrow H$ so that $F \subset \tilde{f}(V)$. Thus the desired result holds. \square

Since we are interested in measure-theoretic results up to sets of measure zero we provide a corollary to Theorem 5.0.1.

Corollary 5.0.1. *Let μ be a locally finite Borel measure on H , V be an m -dimensional linear plane in H , $\alpha \in (0, 1)$, and $0 < r < \infty$. If for μ -a.e. $x \in H$*

$$\mu(C_{\mathcal{B}}(x, r, V, \alpha)) = 0 \tag{5.0.1}$$

then μ is carried by m -Lipschitz graphs.

Proof. Let F denote the set of $x \in H$ that satisfy (5.0.1). We may assume $F \subset B(0, r/2)$; otherwise we may write F as a union of countably many sufficiently small sets and show that each

one is m -graph rectifiable. Let $\{x_i\}$ be a countable dense subset of F . It follows from (5.0.1) and the containment $F \subset B(0, r/2)$ that for each x_i there exists $F_i \subset F$ such that

$$F_i \cap C_{\mathcal{B}}(x_i, r, V, \alpha) = F_i \cap C_{\mathcal{B}}(x_i, V, \alpha) = \emptyset$$

and $\mu(F \setminus F_i) = 0$. Define $F' := \bigcap_{i=1}^{\infty} F_i$. Then

$$\mu(F \setminus F') = \mu\left(F \setminus \bigcap_{i=1}^{\infty} F_i\right) = \mu\left(\bigcup_{i=1}^{\infty} F \setminus F_i\right) \leq \sum_{i=1}^{\infty} \mu(F \setminus F_i) = 0.$$

We claim that $F' \cap C_{\mathcal{B}}(x, V, \alpha) = \emptyset$ for every $x \in F'$. Fix $x \in F'$, and let $y \in C_{\mathcal{B}}(x, V, \alpha)$. By definition of bad cone we have that $\text{dist}(y - x, V) > \alpha|y - x|$. Now let $\epsilon > 0$ such that $\text{dist}(y - x, V) \geq \alpha(|y - x| + \epsilon)$. Recalling that $0 < \alpha < 1$, choose x_i such that $|x_i - x| < \alpha\epsilon/2 < \epsilon/2$. Then

$$\begin{aligned} \text{dist}(y - x_i, V) &\geq \text{dist}(y - x, V) - |x - x_i| \\ &\geq \alpha(|y - x| + \epsilon) - \alpha(\epsilon/2) \\ &= \alpha(|y - x| + \epsilon/2) \\ &> \alpha(|y - x| + |x_i - x|) \\ &\geq \alpha(|y - x_i|). \end{aligned}$$

In particular, we conclude that $y \in C_{\mathcal{B}}(x_i, V, \alpha)$. Since $F_i \cap C_{\mathcal{B}}(x_i, V, \alpha) = \emptyset$, it must be that case that $y \notin F_i$. It follows that $y \notin F'$, and thus $F' \cap C_{\mathcal{B}}(x, V, \alpha) = \emptyset$ for all $x \in F'$. By an application of Theorem 5.0.1 we conclude that there exists an m -Lipschitz graph Γ such that $F' \subset \Gamma$, so $\mu(F \setminus \Gamma) = 0$. \square

Lemma 5.0.1. *Let $x \in H$, $\alpha \in (0, 1)$, and V be an m -dimensional linear plane. If $y \in$*

$C_B(x, V, \alpha + \frac{1-\alpha}{2})$ then there exists some constant η_α depending on at most α and the dimension of the space, n , such that $B(y, \eta_\alpha d) \subset C_B(x, V, \alpha)$ where $d := |x - y|$.

Proof. Set $\eta_\alpha = (1-\alpha)/4$. We claim that if $y \in C_B(x, V, \alpha + \frac{1-\alpha}{2})$ then $B(y, \eta_\alpha d) \subset C_B(x, V, \alpha)$. It suffice to prove the result when $y \in \partial C_B(x, V, \alpha + \frac{1-\alpha}{2})$. In that case,

$$\text{dist}(y - x, V) = \left(\alpha + \frac{1-\alpha}{2} \right) |x - y| = \left(\alpha + \frac{1-\alpha}{2} \right) d.$$

Let $z \in B(y, \frac{1-\alpha}{4}|x - y|)$. Then $|y - x| - \frac{1-\alpha}{4}|y - x| \leq |z - x| \leq |y - x| + \frac{1-\alpha}{4}|y - x|$. In particular,

$$\frac{|z - x|}{1 + \frac{1-\alpha}{4}} \leq |y - x|.$$

Then

$$\begin{aligned} \text{dist}(z - x, V) &\geq \text{dist}(y - x, V) - |y - z| \\ &\geq \left(\alpha + \frac{1-\alpha}{2} \right) |y - x| - \frac{1-\alpha}{4} |y - x| \\ &= \left(\alpha + \frac{1-\alpha}{4} \right) |y - x| \\ &\geq \frac{\left(\alpha + \frac{1-\alpha}{4} \right)}{1 + \frac{1-\alpha}{4}} |z - x| \\ &= \frac{3\alpha + 1}{5 - \alpha} |z - x| \\ &> \alpha |z - x| \end{aligned}$$

for $\alpha \in (0, 1)$. Therefore $z \in C_B(x, V, \alpha)$. Since $z \in B(y, \frac{1-\alpha}{4}|x - y|)$ arbitrary, $\eta_\alpha = \frac{1-\alpha}{4}$ satisfies the desired properties. \square

With the above results established, we now prove a lemma that forms the central argument for the proof of the sufficient condition of Theorem D.

Lemma 5.0.2. *Let μ be a locally finite Borel measure on H . For $x_0 \in H$, V an m -dimensional linear plane, $\alpha \in (0, 1)$, and parameter $K > 0$, let E denote the set of points $x \in H$ such that*

(i) *The sequence of functions*

$$f_r(x) := \frac{\mu(C_{\mathcal{B}}(x, r, V, \alpha))}{\mu(B(x, r))}$$

converges to 0 uniformly on E , and

(ii) *there exists $r_1 > 0$ such that at every $x \in E$,*

$$\mu(B(x, 2r)) \leq K\mu(B(x, r)) \text{ for all } r \in (0, r_1].$$

Then E is μ -carried by m -Lipschitz graphs with Lipschitz constants depending on at most K and α .

Proof. Fix $\delta > 0$. By uniform convergence, choose $r_\delta \leq r_1$ such that for all $r < r_\delta$ and for all $x \in E$,

$$\frac{\mu(C_{\mathcal{B}}(x, 2r, V, \alpha))}{\mu(B(x, 2r))} < \delta. \quad (5.0.2)$$

Fix $x \in E$, and define $S := E \cap C_{\mathcal{B}}(x, r, V, 2\alpha)$. Assuming the set is non-empty, fix $y_0 \in S$ such that $|x - y_0| = \max_{y \in S} |x - y| =: \lambda r$ for some $0 < \lambda \leq 1$. As an application of Lemma 5.0.1 choose η_α such that $B(y_0, \eta_\alpha \lambda r) \subset C_{\mathcal{B}}(x, 2r, V, \alpha)$. Let $d = \log_2 \left(\frac{\lambda+2}{\eta_\alpha \lambda} \right)$. Then

$$2^d \eta_\alpha \lambda r = \frac{\lambda+2}{\eta_\alpha \lambda} \eta_\alpha \lambda r = (\lambda+2)r = |x - y_0|r + 2r.$$

In particular, for the specified value of d , $B(x, 2r) \subset B(y_0, 2^d \eta_\alpha \lambda r)$. Applying condition (ii) of the set E at the point y_0 we see that

$$\mu(C_{\mathcal{B}}(x, 2r, V, \alpha)) \geq \mu(B(x, \eta_\alpha \lambda r)) \geq K^{-d} \mu(B(y_0, 2^d \eta_\alpha \lambda r)) \geq K^{-d} \mu(B(x, 2r)) \quad (5.0.3)$$

Combining inequalities (5.0.2) and (5.0.3), we get the density ratio bounds

$$\delta > \frac{\mu(C_{\mathcal{B}}(x, 2r, V, \alpha))}{\mu(B(x, 2r))} \geq K^{-d}$$

for all $r < r_\delta$. In particular, this implies that $d > \frac{-\log(\delta)}{\log K}$. Equivalently,

$$\log \left(\frac{\lambda + 2}{\eta_\alpha \lambda} \right) > \frac{-\log \delta}{\log K},$$

so that if δ is chosen to be less than $2^{-\log K \log(\frac{5}{\eta_\alpha})}$ then $\lambda < \frac{1}{2}$. From this result we conclude that for $r < r_\delta$ and for all $y \in S$, $|x - y| < \frac{1}{2}r$. Letting $r \downarrow 0$ we conclude that $\mu(E \cap C_{\mathcal{B}}(x, r_\delta, V, 2\alpha)) = 0$. Thus we can apply Corollary 5.0.1 to conclude that $E \cap B(x, r_\delta)$ is contained $\mu - a.e.$ in countably many Lipschitz graphs. By the separability of H , we can choose countably many balls $B(x, r_\delta)$ to cover E , and the result follows. \square

With Lemma 5.0.2 established, we are ready to prove Theorem D.

Proof. We first show the sufficient condition holds. To do so, we use a series of countable decompositions to reduce to a setting in which Lemma 5.0.2 can be applied. First we may assume that μ is a finite measure, for if μ is not finite then by separability of H we may write H as a countable union of closed balls of radius 1. It follows from our definition of pointwise doubling measures that μ is finite on each ball in the union. Then the proof proceeds as below by considering the restriction of μ to each ball.

Choose $\{V_i\}_{i=1}^\infty$ to be a dense collection of m -dimensional linear planes in H and $\{\alpha_j\}_{j=1}^\infty$ to be a sequence dense in $(0, 1)$. For a fixed $\alpha \in (0, 1)$ and m -dimensional linear plane V , we can find $\alpha_k > \alpha$ and V_l such that $\|V_l - V\| < \alpha_k - \alpha$. Then we have $C_{\mathcal{B}}(x, V, \alpha) \subset C_{\mathcal{B}}(x, V_l, \alpha_k)$, so

of course

$$\text{if } \lim_{r \downarrow 0} \frac{\mu(C_{\mathcal{B}}(x, r, V, \alpha))}{\mu(B(x, r))} = 0 \text{ then } \lim_{r \downarrow 0} \frac{\mu(C_{\mathcal{B}}(x, r, V_l, \alpha_k))}{\mu(B(x, r))} = 0. \quad (5.0.4)$$

Now fix some k and l , and let

$$E_{k,l} := \left\{ x \in H : \lim_{r \downarrow 0} \frac{\mu(C_{\mathcal{B}}(x, r, V_l, \alpha_k))}{\mu(B(x, r))} = 0 \right\}.$$

By Egorov's Theorem, choose a measurable subset $E_{k,l,t} \subset E_{k,l}$ such that $\mu(E_{k,l} \setminus E_{k,l,t}) < 2^{-t}$ and

$$f_r^{k,l}(x) := \frac{\mu(C_{\mathcal{B}}(x, r, V_l, \alpha_k))}{\mu(B(x, r))}$$

converges uniformly to zero on $E_{k,l,t}$. Note that $H = \bigcup_{t=1}^{\infty} \bigcup_{l=1}^{\infty} \bigcup_{k=1}^{\infty} E_{k,l,t}$ so it suffices to show that $E_{k,l,t}$ is graph rectifiable for fixed k, l , and t . Next, since μ is pointwise doubling, for μ -a.e. $x \in E_{k,l,t}$, there exists $K_x, N_x \in \mathbb{N}$ such that $\mu(B(x, 2r)) \leq K_x \mu(B(x, r))$ for all $0 < r \leq 1/N_x$.

Define

$$E_{k,l,t}^{K,N} = \{y \in E_{k,l,t} : \mu(B(y, 2r)) \leq K \mu(B(y, r)) \text{ for all } 0 < r \leq 1/N\}.$$

Then $\mu(E_{k,l,t} \setminus \bigcup_{K=1}^{\infty} \bigcup_{N=1}^{\infty} E_{k,l,t}^{K,N}) = 0$. Finally, recall by Theorem 2.1.1 that for μ -a.e. $x \in E_{k,l,t}^{K,N}$,

$$\lim_{r \downarrow 0} \frac{\mu(E_{k,l,t}^{K,N} \cap B(x, r))}{\mu(B(x, r))} = 1.$$

Define

$$E_{k,l,t,p}^{K,N} = \left\{ x \in E_{k,l,t}^{K,N} : \mu(E_{k,l,t}^{K,N} \cap B(x, r)) \geq \frac{1}{2} \mu(B(x, r)) \text{ for all } 0 \leq r \leq 1/p \right\},$$

and note that $E_{k,l,t}^{K,N} = \bigcup_{p=1}^{\infty} E_{k,l,t,p}^{K,N}$. To conclude the proof, apply Lemma 5.0.2 for some fixed k, l, t, K, N and p .

To show the necessary condition, suppose that μ is m -Lipschitz graph rectifiable, and let $\{\Gamma_i\}$ denote a collection of Lipschitz graphs that carry μ . To each graph Γ_i we associate an m -plane V_i and a number $\alpha_i \in (0, 1)$ such that Γ_i is a Lipschitz graph with respect to V_i and α_i . Let $x \in H$ be a μ -density point. Since each graph Γ_i is closed, $x \in \Gamma_i$ for some i . It follows that

$$\lim_{r \downarrow 0} \frac{\mu(B(x, r) \setminus \Gamma_i)}{\mu(B(x, r))} = 0.$$

Furthermore, $\Gamma_i \subset C_{\mathcal{G}}(x, V_i, \alpha_i)$, and so $C_{\mathcal{B}}(x, r, V_i, \alpha_i) \subset B(x, r) \setminus \Gamma_i$. It follows immediately that

$$\lim_{r \downarrow 0} \frac{\mu(C_{\mathcal{B}}(x, r, V_i, \alpha_i))}{\mu(B(x, r))} = 0.$$

This completes the proof of the necessary condition. □

Chapter 6

Hölder parametrization and fractional rectifiability

In this chapter we prove Theorem E.

6.1 Hölder curves through nets

Recall that Theorem 1.3.1 is a Traveling Salesman theorem which provides a sufficient condition under which a sequence of nets is contained in a Hölder curve. We remind the reader that the nets satisfy the following properties:

(V0') When $k = 0$, we have $\rho_0 = 1$. For all $k \geq 0$, we have $\xi_1 \rho_k \leq \rho_{k+1} \leq \xi_2 \rho_k$.

(V1') When $k = 0$, we have $V_0 \subset B(x_0, C^* r_0)$.

(V2') For all $k \geq 0$, we have $V_k \subset V_{k+1}$.

(V3') For all $k \geq 0$ and all distinct $v, v' \in V_k$, we have $|v - v'| \geq \rho_k r_0$.

(V4') For all $k \geq 0$ and all $v \in V_{k+1}$, there exists $v' \in V_k$ such that $|v - v'| < C^* \rho_{k+1} r_0$.

(V5') For each $k \geq 0$ and $v \in V_k$ we are given a number $\alpha_{k,v} \geq 0$ and a straight line $\ell_{k,v}$ in H such that

$$\sup_{x \in V_{k+1} \cap B(v, 30A^* \rho_k r_0)} \text{dist}(x, \ell_{k,v}) \leq \alpha_{k,v} \rho_{k+1} r_0.$$

Here $A^* = C^*/(1 - \xi_2)$.

We state a corollary to Theorem 1.3.1 which we will use in the proof of Theorem E. As was the case with Theorem 1.3.1, we omit the proof.

Corollary 6.1.1 ([6, Corollary 5.5]). *For all $s > 1$, $C^* \geq 1$, and $0 < \xi_1 < \xi_2 < 1$, there exists $\alpha^* > 0$ with the following property. Let $\mathcal{V} = (V_k, \rho_k)_{k \geq 0}$ be a sequence of finite sets V_k in H and numbers $\rho_k > 0$ that satisfy properties (V0')-(V5'). If*

$$S_{\mathcal{V}}^{s,p} := \sum_{k=0}^{\infty} \sum_{v \in V_k} \alpha_{k,v}^p \rho_k^s < \infty \quad \text{for some } p > 0,$$

then there exists a $(1/s)$ -Hölder map $f : [0, 1] \rightarrow H$ such that $\bigcup_{k \geq 0} V_k \subset f([0, 1])$ and the Hölder constant of f satisfies $h_f \lesssim_{s, C^, \xi_1, \xi_2} r_0 (1 + (\alpha^*)^{-p} S_{\mathcal{V}}^{s,p})$.*

6.2 Fractional rectifiability of measures

Now we turn to a lemma which is the core measure-theoretic argument in the proof of Theorem E.

Lemma 6.2.1. *Let μ be a pointwise doubling measure in H , and let $s > 1$ and $p, q > 0$ be fixed. Given $x_0 \in H$ and parameters $M > 0$, $\theta > 0$, and $D > 0$, let A denote the set of points*

$x \in B(x_0, 1/2)$ such that

$$\int_0^1 \beta_p^{(1)}(\mu, x, r)^q \frac{r^s}{\mu(B(x, r))} \frac{dr}{r} \leq M, \quad (6.2.1)$$

$$\mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for all } r \in (0, 1],$$

and let A' denote the set of points in A such that

$$\mu(A \cap B(x, r)) \geq \theta\mu(B(x, r)) \text{ for all } r \in (0, 1].$$

Then A' is contained in a $(1/s)$ -Hölder curve $\Gamma = f([0, 1])$ with Hölder constant depending on at most s, p, q, M, D, θ , and $\mu(A)$.

Proof. Let $\{A'_k\}_{k \geq 0}$ be a nested sequence of 2^{-k} -nets in A' , so that the sets $V_k \equiv A'_k$ and scales $\rho_k = 2^{-k}$ satisfy conditions (V0')–(V5') with parameters $r_0 = 1, C^* = 2, \xi_1 = \xi_2 = 1/2$. Note that $A^* = C^*/(1 - \xi_2) = 4$ and $30A^* = 120$. It is an easy exercise using the doubling and lower regularity properties on the set A to show that the cardinality of A'_k is bounded by D^{k+2}/θ , and in particular the cardinality is finite for each k .

By (6.2.1),

$$\begin{aligned} M\mu(A) &\geq \int_A \int_0^1 \beta_p^{(1)}(\mu, x, r)^q \frac{r^s}{\mu(B(x, r))} \frac{dr}{r} d\mu(x) \\ &= \sum_{k=9}^{\infty} \int_{2^{-(k+1)}}^{2^{-k}} (512r)^s \int_A \frac{\beta_p^{(1)}(\mu, x, 512r)^q}{\mu(B(x, 512r))} d\mu(x) \frac{dr}{r} \end{aligned}$$

where in the second line we used the change of variables $r \mapsto 512r$ (note $512 = 2^9$) and Tonelli's theorem. Now, the open balls $\{B(y, 2^{-(k+1)}) : y \in A'_k\}$ are pairwise disjoint, because the points

in A'_k are separated by distance at least 2^{-k} . Thus,

$$M\mu(A) \geq \sum_{k=9}^{\infty} \int_{2^{-(k+1)}}^{2^{-k}} r^s \sum_{y \in A'_k} \underbrace{\int_{A \cap B(y, 2^{-(k+1)})} \frac{\beta_p^{(1)}(\mu, x, 512r)^q}{\mu(B(x, 512r))} d\mu(x)}_{I(k, y, r)} \frac{dr}{r}. \quad (6.2.2)$$

Next, we bound $I(k, y, r)$ from below. Fix $k \geq 9$, $y \in A'_k$, and $r \in [2^{-(k+1)}, 2^{-k}]$. Suppose that $x \in A \cap B(y, 2^{-(k+1)})$. Then

$$\mu(B(x, 512r)) \leq D^2 \mu(B(x, 128r)) \leq D^2 \mu(B(y, 129r)) \leq D^2 \mu(B(y, 255 \cdot 2^{-k})) \quad (6.2.3)$$

by (6.2.1). Since $B(y, 255 \cdot 2^{-k}) \subset B(x, 256 \cdot 2^{-k}) \subset B(x, 512r)$, it follows that

$$\begin{aligned} \beta_p^{(1)}(y, 255 \cdot 2^{-k}) &\leq \left(\frac{512r}{255 \cdot 2^{-k}} \right) \left(\frac{\mu(B(x, 512r))}{\mu(B(y, 255 \cdot 2^{-k}))} \right)^{1/p} \beta_p^{(1)}(\mu, x, 512r) \\ &\leq 3D^{2/p} \beta_p^{(1)}(\mu, x, 512r). \end{aligned}$$

The last inequality holds since an expansion of the definition of $\beta_p^{(m)}(\mu, x, r)$ shows that

$$s\mu(B(y, s))^{1/p} \beta_p^{(m)}(\mu, y, s) \leq r\mu(B(x, r))^{1/p} \beta_p^{(m)}(\mu, x, r) \quad \text{when } B(y, s) \subset B(x, r). \quad (6.2.4)$$

Hence

$$I(k, y, r) \geq 3^{-q} P^{-2-2q/p} \frac{\beta_p^{(1)}(\mu, y, 255 \cdot 2^{-k})^q}{\mu(B(y, 255 \cdot 2^{-k}))} \int_{A \cap B(y, 2^{-(k+1)})} d\mu(x).$$

Invoking doubling again, $\mu(B(y, 255 \cdot 2^{-k})) \leq D^9 \mu(B(y, 2^{-(k+1)}))$. Thus, by (6.2.1),

$$\frac{1}{\mu(B(y, 255 \cdot 2^{-k}))} \int_{A \cap B(y, 2^{-(k+1)})} d\mu(x) \geq D^{-9} \frac{\mu(A \cap B(y, 2^{-(k+1)}))}{\mu(B(y, 2^{-(k+1)}))} \geq D^{-9} \theta.$$

Therefore,

$$I(k, y, r) \geq 3^{-q} D^{-11-2q/p} \theta \beta_p^{(1)}(\mu, y, 255 \cdot 2^{-k})^q \quad (6.2.5)$$

Combining (6.2.2) and (6.2.5), we obtain

$$3^q D^{11+2q/p} \theta^{-1} M\mu(A) \geq \sum_{k=9}^{\infty} \left(\int_{2^{-(k+1)}}^{2^{-k}} r^s \frac{dr}{r} \right) \sum_{y \in A'_k} \beta_p^{(1)}(\mu, y, 255 \cdot 2^{-k})^q.$$

In particular, we conclude that

$$\sum_{k=9}^{\infty} \sum_{y \in A'_k} \beta_p^{(1)}(\mu, y, 255 \cdot 2^{-k})^q 2^{-ks} \leq \frac{s}{1-2^{-s}} 3^q D^{11+2q/p} \theta^{-1} M\mu(A) < \infty$$

For each $k \geq 9$ and $y \in A'_k$, let $\ell_{k,v}$ be any line such that

$$\beta_p^{(1)}(\mu, y, 255 \cdot 2^{-k}, \ell_{k,v}) \leq 2\beta_p^{(1)}(\mu, y, 255 \cdot 2^{-k}).$$

We will now bound the distance of points in $A'_{k+1} \cap B(y, 120 \cdot 2^{-k})$ to $\ell_{k,v}$. Fix any point $z \in A'_{k+1} \cap B(y, 120 \cdot 2^{-k})$ and let $t2^{-k+1} = \text{dist}(z, \ell_{k,v})$. Then

$$\begin{aligned} \beta_p(\mu, y, 255 \cdot 2^{-k}, \ell_{k,v})^q &\geq \left(\frac{\frac{1}{2}t2^{-(k+1)}}{255 \cdot 2^{-k}} \right)^q \left(\frac{\mu(B(z, \frac{1}{2}t2^{-(k+1)}))}{\mu(B(y, 255 \cdot 2^{-k}))} \right)^{q/p} \\ &\geq \left(\frac{t}{1020} \right)^q D^{-(q/p) \log_2(1920/t)} \geq \left(\frac{t}{1920} \right)^{q+(q/p) \log_2(D)}, \end{aligned}$$

where in the second line we used doubling of μ at z . It follows that

$$\alpha_{k,v} := 2^{k+1} \sup_{z \in A'_{k+1} \cap B(y, 120 \cdot 2^{-k})} \text{dist}(z, \ell_{k,v}) \leq C(p, q, D) \beta_p(\mu, y, 255 \cdot 2^{-k}, \ell_{k,v})^\eta,$$

where $\eta[q + (q/p) \log_2(D)] = q$. Therefore, all together,

$$\sum_{k=9}^{\infty} \sum_{y \in A'_k} \alpha_{k,v}^{q+(q/p) \log_2(D)} 2^{-ks} \leq C(s, p, q, M, D, \theta, \mu(A)) < \infty.$$

Finally, by Corollary 6.1.1, the set A' is contained in the Hausdorff limit of A'_k and this is contained in a $(1/s)$ -Hölder curve $\Gamma = f([0, 1])$ with Hölder constant depending on at most s, p, q, M, D, θ , and $\mu(A)$. \square

We are now ready to prove Theorem E.

Proof of Theorem E. Let

$$E = \left\{ x \in H : \int_0^1 \beta_p^{(1)}(\mu, x, r)^q \frac{r^s}{\mu(B(x, r))} \frac{dr}{r} < \infty \right\}.$$

Set

$$E^M = \left\{ x \in E : \int_0^1 \beta_p^{(1)}(\mu, x, r)^p \frac{r^s}{\mu(B(x, r))} \frac{dr}{r} \leq M \right\}.$$

By assumption $E = \bigcup_{M=1}^{\infty} E^M$. Next let

$$E_D^M = \{ x \in E^M : \mu(B(x, 2r)) \leq D\mu(B(x, r)) \text{ for all } r \in (0, 1] \}.$$

Then by the pointwise doubling property on points in E , $E^M = \bigcup_{D=1}^{\infty} E_D^M$ for each M . Finally, by Theorem 2.1.1 $\mu(E_D^M \setminus \bigcup_{k=1}^{\infty} E_{D,k}^M) = 0$, where

$$E_{D,k}^M = \left\{ x \in E_D^M : \mu(E_D^M \cap B(x, r)) \geq \frac{1}{k} \mu(B(x, r)) \text{ for all } r \in (0, 1] \right\}.$$

Combining the above results we see that

$$\mu \left(E \setminus \bigcup_{M=1}^{\infty} \bigcup_{D=1}^{\infty} \bigcup_{k=1}^{\infty} E_{D,k}^M \right) = 0.$$

Now by the separability of H , for each M, D, k , we can cover $E_{D,k}^M$ with a countable union of balls $\{B(x_i, 1/2)\}$ where $x_i \in E_{D,k}^M$. Then we can apply Lemma 6.2.1 to $A = E_{D,k}^M \cap B(x_i, 1/2)$ for each i . □

Bibliography

- [1] Murat Akman, Jonas Azzam, and Mihalis Mourgoglou, *Absolute continuity of harmonic measure for domains with lower regular boundaries*, Adv. Math. **345** (2019), 1206–1252. MR 3903916
- [2] Giovanni Alberti and Martino Ottolini, *On the structure of continua with finite length and Golab’s semicontinuity theorem*, Nonlinear Anal. **153** (2017), 35–55. MR 3614660
- [3] Jonas Azzam and Xavier Tolsa, *Characterization of n -rectifiability in terms of Jones’ square function: Part II*, Geom. Funct. Anal. **25** (2015), no. 5, 1371–1412. MR 3426057
- [4] Jonas Azzam, Xavier Tolsa, and Tatiana Toro, *Characterization of rectifiable measures in terms of α -numbers*, (2018), preprint, arXiv:1808.07661.
- [5] Matthew Badger, *Generalized rectifiability of measures and the identification problem*, Complex Anal. Synerg. **5** (2019), no. 1, Paper No. 2, 17. MR 3941625
- [6] Matthew Badger, Lisa Naples, and Vyron Vellis, *Hölder curves and parameterizations in the analyst’s traveling salesman theorem*, Adv. Math. **349** (2019), 564–647. MR 3941391
- [7] Matthew Badger and Raanan Schul, *Multiscale analysis of 1-rectifiable measures: necessary conditions*, Math. Ann. **361** (2015), no. 3-4, 1055–1072. MR 3319560

- [8] ———, *Multiscale analysis of 1-rectifiable measures II: Characterizations*, Anal. Geom. Metr. Spaces **5** (2017), no. 1, 1–39. MR 3627148
- [9] Gerald Beer, *Topologies on closed and closed convex sets*, Mathematics and its Applications, vol. 268, Kluwer Academic Publishers Group, Dordrecht, 1993. MR 1269778
- [10] A. S. Besicovitch, *On the fundamental geometrical properties of linearly measurable plane sets of points*, Math. Ann. **98** (1928), no. 1, 422–464. MR 1512414
- [11] Marianna Csörnyei, Antti Käenmäki, Tapio Rajala, and Ville Suomala, *Upper conical density results for general measures on \mathbb{R}^n* , Proc. Edinb. Math. Soc. (2) **53** (2010), no. 2, 311–331. MR 2653235
- [12] Damian Dabrowski, *Necessary condition for rectifiability involving Wasserstein distance w_2* , (2019), preprint, arXiv:1904.11000.
- [13] ———, *Sufficient condition for rectifiability involving Wasserstein distance w_2* , 2019, preprint, arXiv:1904.11004.
- [14] G. David and S. Semmes, *Singular integrals and rectifiable sets in \mathbb{R}^n : Beyond Lipschitz graphs*, Astérisque (1991), no. 193, 152. MR 1113517
- [15] Guy David and Stephen Semmes, *Analysis of and on uniformly rectifiable sets*, Mathematical Surveys and Monographs, vol. 38, American Mathematical Society, Providence, RI, 1993. MR 1251061
- [16] Herbert Federer, *The (φ, k) rectifiable subsets of n -space*, Trans. Amer. Math. Soc. **62** (1947), 114–192. MR 22594
- [17] ———, *Geometric measure theory*, Die Grundlehren der mathematischen Wissenschaften, Band 153, Springer-Verlag New York Inc., New York, 1969. MR 0257325

- [18] John Garnett, Rowan Killip, and Raanan Schul, *A doubling measure on \mathbb{R}^d can charge a rectifiable curve*, Proc. Amer. Math. Soc. **138** (2010), no. 5, 1673–1679. MR 2587452
- [19] Juha Heinonen, *Lectures on analysis on metric spaces*, Universitext, Springer-Verlag, New York, 2001. MR 1800917
- [20] Peter W. Jones, *Rectifiable sets and the traveling salesman problem*, Invent. Math. **102** (1990), no. 1, 1–15. MR 1069238
- [21] Antti Käenmäki and Ville Suomala, *Conical upper density theorems and porosity of measures*, Adv. Math. **217** (2008), no. 3, 952–966. MR 2383891
- [22] ———, *Nonsymmetric conical upper density and k -porosity*, Trans. Amer. Math. Soc. **363** (2011), no. 3, 1183–1195. MR 2737262
- [23] Gilad Lerman, *Quantifying curvelike structures of measures by using L_2 Jones quantities*, Comm. Pure Appl. Math. **56** (2003), no. 9, 1294–1365. MR 1980856
- [24] Miguel Ángel Martín and Pertti Mattila, *k -dimensional regularity classifications for s -fractals*, Trans. Amer. Math. Soc. **305** (1988), no. 1, 293–315. MR 920160
- [25] Pertti Mattila, *Hausdorff m regular and rectifiable sets in n -space*, Trans. Amer. Math. Soc. **205** (1975), 263–274. MR 357741
- [26] ———, *Geometry of sets and measures in Euclidean spaces*, Cambridge Studies in Advanced Mathematics, vol. 44, Cambridge University Press, Cambridge, 1995, Fractals and rectifiability. MR 1333890
- [27] A. P. Morse and John F. Randolph, *The ϕ rectifiable subsets of the plane*, Trans. Amer. Math. Soc. **55** (1944), 236–305. MR 9975

- [28] Kate Okikiolu, *Characterization of subsets of rectifiable curves in \mathbf{R}^n* , J. London Math. Soc. (2) **46** (1992), no. 2, 336–348. MR 1182488
- [29] David Preiss, *Geometry of measures in \mathbf{R}^n : distribution, rectifiability, and densities*, Ann. of Math. (2) **125** (1987), no. 3, 537–643. MR 890162
- [30] Raanan Schul, *Subsets of rectifiable curves in Hilbert space—the analyst’s TSP*, J. Anal. Math. **103** (2007), 331–375. MR 2373273